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DEVELOPMENT OF A CLEAN AIR FIRE
TRAINING FUEL



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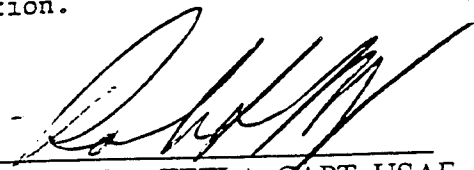
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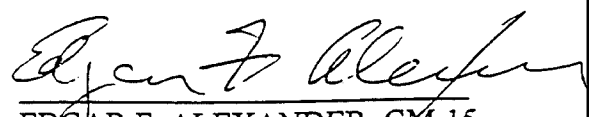
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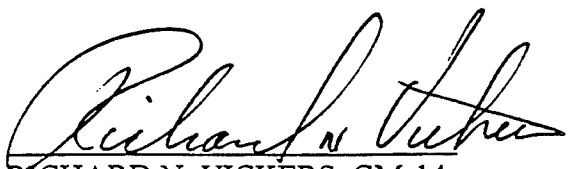
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PREFACE

This report was prepared by Professor J. Brian A. Mitchell of the Department of Physics, University of Western Ontario, London, Ontario, Canada N6A 3K7 under subcontract no. S-5000.5 with Applied Research Associates, Inc., 4300 San Mateo Blvd., NE, Suite A220, Albuquerque, NM 87110, acting under Supplemental Support Group (SSG) Subtask 3.03, of contract number F08635-93-C-0020.

The report summarizes work performed between 1 July 1993 and 28 February 1994. Mr. Charles W. Risinger was the WL/FIVCF Project Manager.

Special thanks are due to Mr. Bruce Irwin and Mr. A.J. Misiti of EXXON Chemical Company for their assistance with this project and to EXXON Chemical Company for supplying the fuel, CD2022.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The primary aim of this program has been to develop a fuel for use in firefighter training that would provide a realistic challenge to the trainee firefighter and yet would present a minimum impact on the environment. In achieving the first goal, a liquid hydrocarbon fuel is most desirable because of its mobile character, safe suppressibility and natural fire appearance. When burned however, liquid hydrocarbon fuels usually emit a wide array of environmental pollutants including Volatile Organic Carbon (VOC) compounds such as benzene and toluene, Aldehydes such as formaldehyde and propionaldehyde and Polycyclic Aromatic Hydrocarbons (PAH's) such as benzo(a)pyrene. Many of these compounds are toxic and/or carcinogenic. In addition to its polluting effects, the smoke plumes generated by fires of conventional fuels are unsightly giving a very negative public image of the fire training enterprise.

B. BACKGROUND

This project evolved out of a program aimed at reducing the emissions from the combustion of oil spills on the ocean. In that situation, one has no choice of fuel nor of any viable means of improving the combustion process by physical means. The method of approach therefore was to use smoke reducing additives to reduce emissions from the large pool fires characteristic of in-situ oil combustion. The effects of additive composition and fuel structure on emission characteristics were studied in a number of different laboratory trials performed at the University of Western Ontario and at the National Research Council of Canada's National Fire Laboratory (NRCC/NFL) using fire scales from a few centimeters up to one meter in diameter. These tests were backed up by large scale trials (up to 20 feet in diameter) held at the Calgary Fire Training Center, and London Civil Airport. Chemical analysis was performed on the emissions from the small scale fires while the large fires provided a visual record of the efficacy of the various additive approaches.

Initially the aim was to clean up the emissions from conventional aviation fuels such as JP4, JP5 and JP8. While it was found in the laboratory that it was possible to reduce the smoke from these fires by about 80%, the large scale tests showed that even this amount produced visually unacceptable smoke plumes. Our concentration turned therefore, to the use of a different fuel that produced low smoke emissions in its neat state and to further improve the performance of this clean fuel by using smoke reducing additive technology. The fuel that was chosen is a proprietary compound of EXXON Chemical Company, designated CD2022.

One meter scale fire tests have been performed on this fuel/additive combination at NRCC/NFL and these have been backed up by large scale trials at Lambton College Industrial Fire School in Sarnia, Ontario and at the Texas A&M University Industrial Fire Training Facility.

C. SCOPE

Previous trials proved to be so successful that a decision was made to take this new fuel/additive combination to the Fire Research Facility at Tyndall Air Force Base (Florida) and to repeat the emissions tests at a 20 foot diameter scale and to use actual firefighting techniques against 100 foot diameter fires of this fuel/additive mixture.

An additional feature of this test series was the study of the emissions arising from fires of conventional JP4 and of the new CD2022/additive mixture while these fires are being exposed to the firefighting agents Aqueous Film Forming Foam (AFFF), Dry Chemical and Halon 1211.

In all these tests, comparisons were made against the emissions from fires of JP4 since this is the standard fuel currently used for fire training purposes in the United States Air Force.

D. CONCLUSIONS

The tests described in this report have shown that a proprietary new fuel, designated CD2022, when mixed with a smoke reducing additive, can produce emissions of particulate, VOC's, PAH's and Aldehydes that are very greatly reduced from those produced with conventional aviation fuels such as JP4, JP5 and JP8. Furthermore, while use of the smoke reducing additive does decrease emissions from these fuels, the size of these decreases is still inferior to that exhibited by the CD2022 fuel.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The primary aim of this program has been to develop a fuel for use in firefighter training that would provide a realistic challenge to the trainee firefighter and yet would present a minimum impact on the environment. In achieving the first goal, a liquid hydrocarbon fuel is most desirable because of its mobile character, safe suppressibility and natural fire appearance. When burned however, liquid hydrocarbon fuels usually emit a wide array of environmental pollutants including Volatile Organic Carbon (VOC) compounds such as benzene and toluene, Aldehydes such as formaldehyde and propionaldehyde and Polycyclic Aromatic Hydrocarbons (PAH's) such as benzo(a)pyrene. Many of these compounds are toxic and/or carcinogenic. In addition to its polluting effects, the smoke plumes generated by fires of conventional fuels are unsightly giving a very negative public image of the fire training enterprise.

B. BACKGROUND

This project evolved out of a program aimed at reducing the emissions from the combustion of oil spills on the ocean. In that situation, one has no choice of fuel nor of any viable means of improving the combustion process by physical means. The method of approach therefore was to use smoke reducing additives to reduce emissions from the large pool fires characteristic of in-situ oil combustion. The effects of additive composition and fuel structure on emission characteristics were studied in a number of different laboratory trials (Refs. 1-4) performed at the University of Western Ontario and at the National Research Council of Canada's National Fire Laboratory (NRCC/NFL) using fire scales from a few centimeters up to one meter in diameter. These tests were backed up by large scale trials (up to 20 feet in diameter) held at the Calgary Fire Training Center, and London Civil Airport. Chemical analysis was performed on the emissions from the small scale fires while the large fires provided a visual record of the efficacy of the various additive approaches.

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One meter scale fire tests have been performed on this fuel/additive combination at NRCC/NFL and these have been backed up by large scale trials at Lambton College Industrial Fire School in Sarnia, Ontario and at the Texas A&M University Industrial Fire Training Facility (Refs.

5,6). These trials proved to be very successful and so a decision was made to take this new fuel/additive combination to the Fire Research Facility at Tyndall Air Force Base (Florida) and to repeat the emissions tests at a 20 foot diameter scale and to use actual firefighting techniques against 100 foot diameter fires of this fuel/additive mixture. These tests are described in this report.

An additional feature of this test series has been the study of the emissions arising from fires of conventional JP4 and of the new CD2022/additive mixture while these fires are being exposed to the firefighting agents Aqueous Film Forming Foam (AFFF), Dry Chemical and Halon 1211.

In all these tests, comparisons have been made against the emissions from fires of JP4 since this is the standard fuel currently used for fire training purposes in the United States Air Force.

SECTION II

CURRENT PROGRAM AND METHODS

A. INTRODUCTION

The testing program conducted to date indicates that the new fuel CD2022 when used with appropriate concentrations of smoke reducing additives shows great promise as a clean burning fire training fuel. The purpose of the work described in this report was to measure the emissions produced from the fuel during 6 feet diameter burn tests; to compare these emissions with conventional fuels such as JP4, JP5 and JP8; and to determine the effects of different additive concentrations on the emissions from these fires. In this respect, this program was similar to other tests performed at the National Research Council of Canada's, National Fire Laboratory (NRCC/NFL) in Canada (Refs. 5,6) albeit at a larger scale. (The NFL tests employed 3 feet diameter burns.) The current study went further, however, for the effects of introducing the fire fighting agents, Aqueous Film Forming Foam (AFFF), Dry Chemical and Halon 1211 into the 6 foot fires were also examined. Tables 1-7 list the various fire tests that were performed.

B. TEST FACILITY

The Controlled Environment Burn Facility at Tyndall Air Force Base (Florida) was used for all the emissions measurements. An external view of this facility is shown in figure 1 and a view of the fire pan and thermocouple array, used for measuring flame temperatures, in figure 2. The facility employs a 6 feet diameter fire pan located just outside a 10 feet diameter, 40 feet high chimney. The top portion of the chimney narrows down to 6 feet. It was found that locating the pan directly underneath the chimney produced too much draft leading to too rapid combustion. This was avoided by offsetting the fire pan from the chimney opening. This arrangement was very successful and tests showed that all the fire plume was drawn up the chimney, without the fire being much affected by the draft.

Soot and gas samples were withdrawn from the top portion of the flue by means of five 3/8-inch diameter copper tubes introduced through the chimney side wall. These tubes were connected to various pump and filter/sorption tube arrangements as shown in figure 3 and schematically in figure 4. A visible beam from a laser diode was directed across the flue and measured with a photodetector and power meter. This arrangement was used to measure the opacity of the fire plume.

Emissions measurements taken during this test series are summarized in Table 8 and discussed in more detail below.

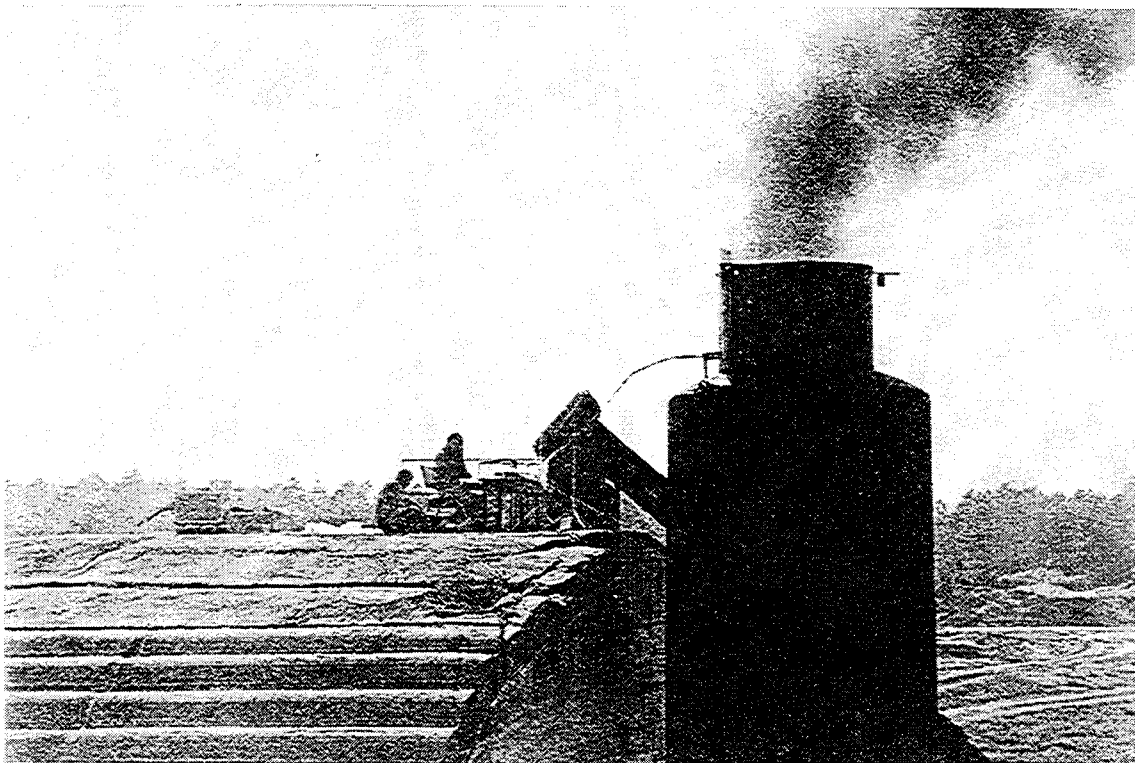


Figure 1. Exterior view of the Controlled Environment Burn Facility. (The gas sampling station is seen next to the top of the smokestack. The thin pipe attached to the stack, draws combustion gases to the sampling apparatus.)

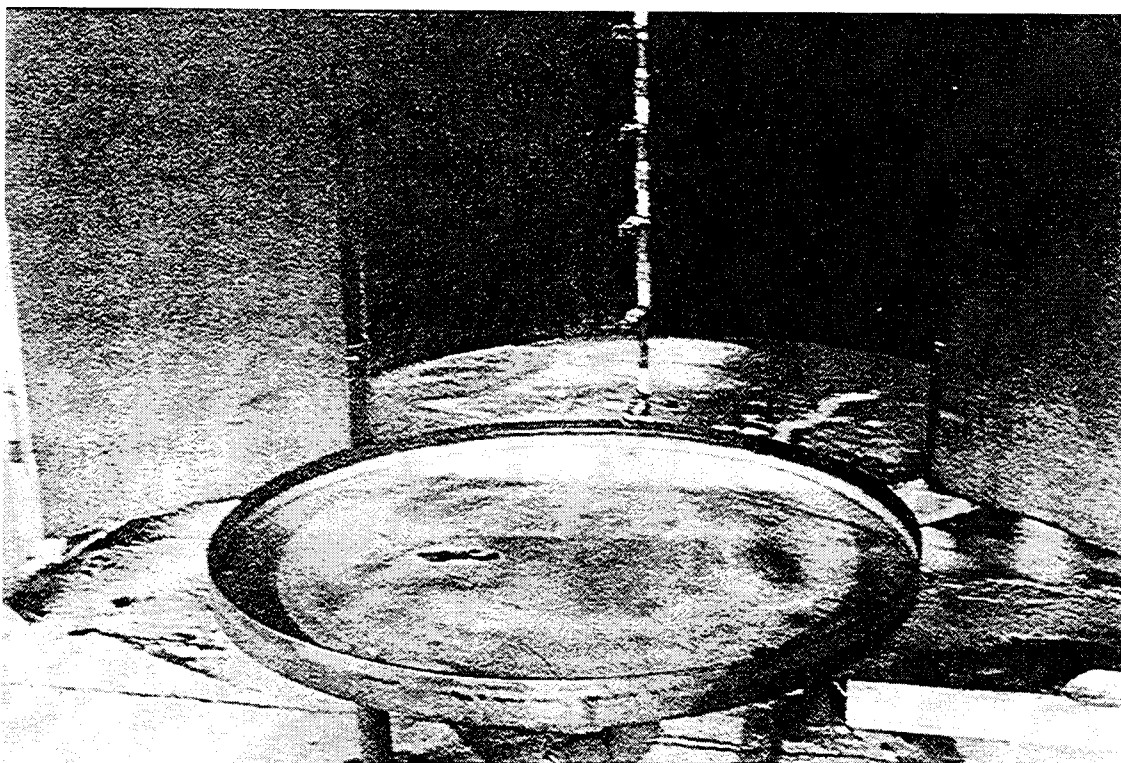


Figure 2. Six foot diameter fire pan with thermocouple tree positioned at the pan edge.

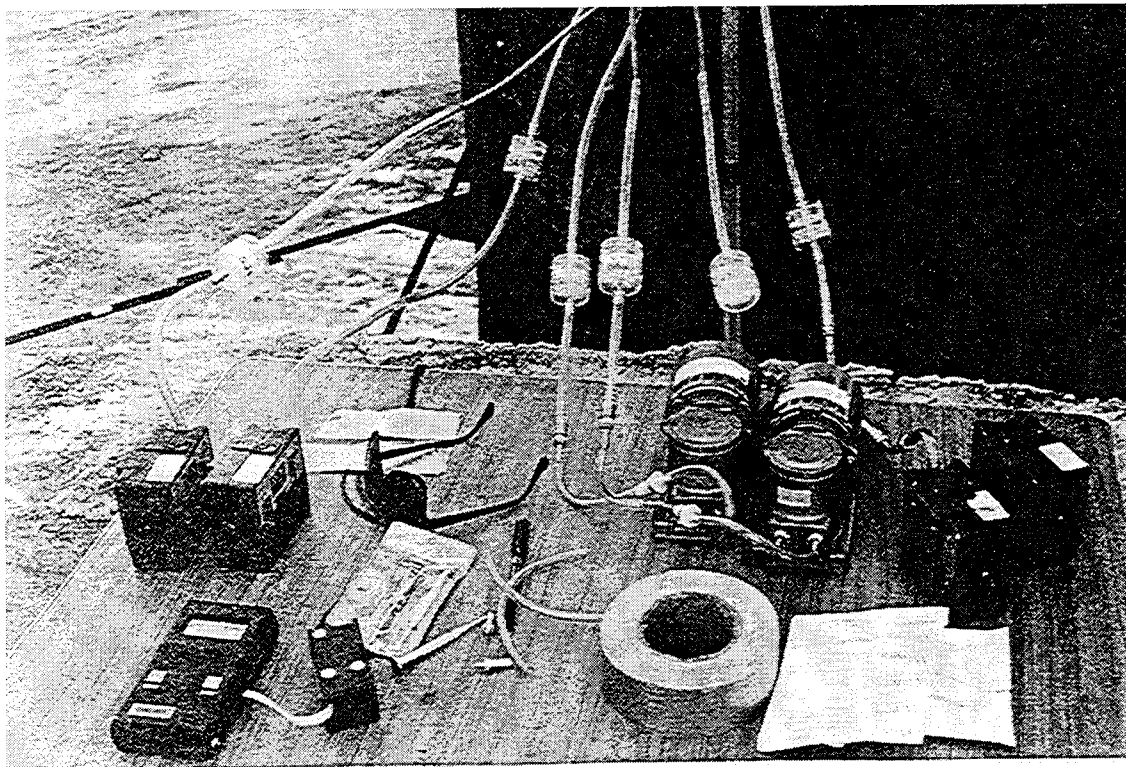


Figure 3. View of the sampling train with Gilian pumps, vacuum pumps, filter cartridges and sorbent tubes.

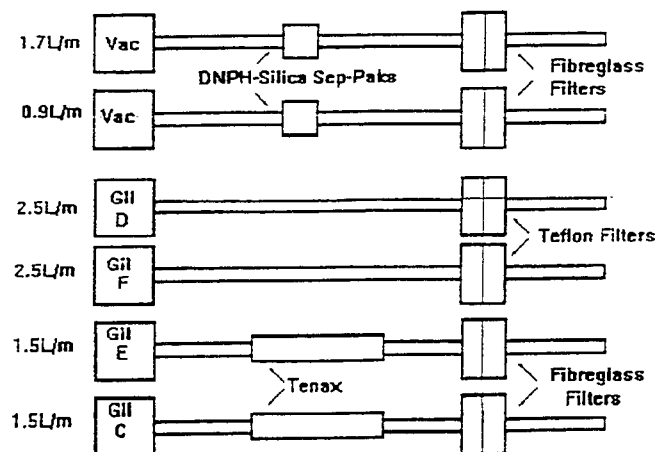


Figure 4. Filter sorption tube gas and particulate collection arrangement.

TABLE 1. NEAT AVIATION FUELS

Test #	Fuel	Quantity (Gallons)	Burn Time (min)
1	JP4	10	14
2	JP5	10	17
3	JP8	10	18

TABLE 2. JP4 PLUS ADDITIVE

Test #	Fuel	Quantity (Gallons)	Burn Time (min)
S2	JP4	10	14
7	JP4 + 0.5% Additive	10	13
5	JP4 + 1.0% Additive	10	13

TABLE 3. JP4 VERSUS CD2022 PLUS ADDITIVE

Test #	Fuel	Quantity (Gallons)	Burn Time (min)
S3	JP4	5	13
S4	JP4	15	13
4	CD2022 Only	10	17
6	CD2022 + 1% Additive	10	17
8	CD2022 + 2% Additive	10	17
9	CD2022 + 0.25% Additive	10	17

TABLE 4. FUELS PLUS AFFF

Test #	Fuel	Agent Quantity (Liters)	Fuel Quantity (Gallons)	Burn Time (min)
10	JP4	16	10	15
12	CD2022 + 1% Additive	8	10	20
14	CD2022 + 0.5% Additive	8	10	17
16	CD2022 + 0.25% Add	8	10	17

TABLE 5. FUELS PLUS DRY CHEMICAL

Test #	Fuel	Agent Quantity (lbs)	Fuel Quantity (Gallons)	Burn Time (min)
11	JP4	34.5	10	10
13	CD2022 + 1% Additive	18.5	10	17
15	CD2022 + 0.5% Additive	25.5	10	17
17	CD2022 + 0.25% Add	19	10	16

TABLE 6. FUELS PLUS HALON 1211

Test #	Fuel	Agent Quantity (Liters)	Fuel Quantity (Gallons)	Burn Time (min)
24	JP4	20.5	10	16
25	CD2022 + 1% Additive	20.5	10	18
26	CD2022 + 0.5% Additive	20	10	16
27	CD2022 + 0.25% Add	20	10	16

TABLE 7. LARGE SCALE TESTS

Test #	Fuel	Test Type	Fuel Quantity (Gallons)	Extinguishment Time (sec)
29	JP4 vs CD2022 + 1% Additive	20 feet side-by-side	110 each	---
30	JP4 vs CD2022 + 0.5% Additive	20 feet side-by-side	110 each	---
31	JP4 vs CD2022 + 0.25% Add	20 feet side-by-side	110 each	---
32	CD2022 + 0.25% Add	20 feet w/ water spray	110	---
33	CD2022 + 0.25% Add	100 feet	330	47
34	CD2022 + 0.25% Add	100 feet	500	23
35	CD2022 + 0.5% Add	100 feet	500	30
36	CD2022 + 0.5% Add	100 feet	500	18
40	CD2022 + 1% Add	100 feet	500	28
41	CD2022 + 1% Add	100 feet	500	59
42	JP4	100 feet	500	30

C. EMISSION AND FIRE CHARACTERISTICS MEASUREMENTS

TABLE 8. EMISSIONS MEASURED AND EXPERIMENTAL METHODS

PARAMETER	METHOD
Relative Soot Yield	Collection on fiberglass and PTFE filters
Relative Opacity of Plume	(i) IR diode and Photodetector in duct, 9 meters from center of hood (ii) Visible laser (620-680 nm) and photodetector
Polycyclic Aromatic Hydrocarbons (PAH's)	Soxhlet extraction from soot samples followed by GC/MS analysis
Aldehydes	Absorption in DNPH, cold solvent extraction of hydrazone derivatives and subsequent GC/MS analysis
Volatile Organic Hydrocarbons (VOC's)	Absorption of exhaust gases in Tenax tubes followed by thermal desorption and GC/MS analysis

1. Soot Mass Measurement

The equipment shown in figure 4 was used to collect soot at known rates from the smoke plume. PTFE and fiberglass filters were used, the exhaust gases being drawn through these filters as shown. The filters were preweighed prior to the testing and weighed again following the tests. In this way soot masses collected were determined. Most of the data presented in this report is relative, comparisons being made with JP4 results since this is the fuel currently in widespread usage in the USAF for firefighter training.

It is possible in principle to determine the total soot yield as a function of fuel mass by measuring the relative amounts of CO₂, CO and soot collected during the experiments with the equipment shown in figure 4. These numbers can then be related back to the total amount of carbon in the fuel. This is known as the "carbon balance method". This was attempted during this series of measurements but unfortunately, the CO₂ and CO analyzers at the WL/FIVCF Fire Research Laboratory at Tyndall AFB were not sufficiently sensitive to provide accurate and meaningful data. Such measurements have been performed successfully elsewhere (Reference 7) and it is found that about 10% of the mass of a hydrocarbon fuel such as JP4 is converted to soot. We can use this figure to provide an estimate of the total emission yields in this experiment.

2. Opacity

The obscuration of light passing through the smoke plume was measured by shining a light beam from a laser diode across the chimney and collecting it on a photodetector connected

to a power meter. Considerable difficulties were encountered with this system as the mechanical alignment of the beam with the photodetector was found to vary during the tests. Good data was obtained for some of the tests but for many others the data was rejected.

In these measurements, the degree of obscuration was determined for each fuel/additive mixture and compared with that for JP4 alone. The percentage reduction in smoke opacity was then determined.

3. Flame Temperatures

A thermocouple tree was mounted at the edge of the 6 feet diameter pan with thermocouples spaced at vertical intervals of 1 foot beginning at the pan lip. These thermocouples were connected to a datalogger.

4. Polycyclic Aromatic Hydrocarbon's (PAH's)

Soot samples were collected during the various tests using the arrangement shown in figures 3 and 4. Each set of filters was placed in a Whatman 25 millimeter inner diameter by 80 millimeter external length cellulose extraction thimble. Ten microliters of anthracene d-10, chrysene d-12, and perylene d-12 recovery solution was then injected onto the soot matrix. One hundred and fifty milliliters of benzene was then placed in a boiling flask, the soxhlet apparatus assembled and refluxing performed for a period of 36 hours for each filter set. The soxhlet solution was then reduced down to 2.0 milliliters using a Kontes evaporation apparatus. Ten microliters of phenanthrene d-10 internal calibration standard was added to the solution and a one microliter sample was injected into a Varian 3400 Gas Chromatograph with a Saturn II Mass Spectrometer detector (GC/MS) for analysis.

Relative concentrations of Polycyclic Aromatic Hydrocarbons (PAHs) in soot samples were determined from the areas under the chromatograph peaks corresponding to each species and these were normalized to the volume of air sampled during each set of measurements. In each case the results obtained were compared to those obtained for JP4. Table 9 provides the legend that correlates the numbers on the baseline of the figures shown in the next sections, with the identity of the PAH compounds.

5. Volatile Organic Carbons (VOC's)

Air samples were taken during the tests using Tenax sorbent tubes (Gilian Hygitest 15/30 milligram) in order to determine the quantities of volatile organic hydrocarbons (VOCs) emitted by the fires. Following collection, the Tenax was removed from the tubes and placed in a 28 milliliter headspace analysis vial. Ten microliters of a 1-bromo-4-fluorobenzene internal calibration standard was then injected onto the matrix, the vial was sealed and then placed in the thermal desorption, headspace analyzer of the GC/MS apparatus.

It was found that benzene, toluene and a number of volatile polycyclic aromatic hydrocarbons were the most abundant VOCs in the emissions.

TABLE 9. POLYCYCLIC AROMATIC HYDROCARBONS MEASURED

#	Compound Name
1	Acenaphthylene
2	1,1 -biphenyl
3	Fluorene
4	Phenanthrene
5	Anthracene
6	Fluoranthene
7	Pyrene
8	Benzo (g, h, i) fluoranthene
9	Benzo (a) anthracene
10	Chrysene/Triphenylene
11	Benzo (b) fluoranthene
12	Benzo (k) fluoranthene
13	Benzo (e) pyrene
14	Benzo (a) pyrene
15	Perylene
16	Indeno (1, 2, 3-cd) pyrene
17	Benzo (g, h, i) perylene
18	Dibenzo (a, h) anthracene

6. Aldehydes

Aldehydes are rapidly photo-oxidized in the environment and a method of fixing them so that they do not degrade is needed in order to perform quantitative analysis of their emission. The compound 2,4-dinitrophenylhydrazine (DNPH) reacts rapidly with aldehydes to form hydrazone adducts that are stable and their concentration can be analyzed. By absorbing the exhaust gases in cartridges containing this material we are able to quantify the aldehyde emissions during these experiments.

Commercially available, Waters Sep-Pak DNPH silica cartridges were used. After gas collection, 360 milligrams of the DNPH material was removed from the cartridges, mixed with 2 milliliters of acetonitrile and agitated for 2 minutes. After being allowed to sit for a further 10 minutes, 10 microliters of a deuterated internal calibration standard was added to the solution. One microliter of the resulting solution was then injected into the GC/MS for analysis.

It was found that only two aldehyde compounds, formaldehyde and propionaldehyde, were detected during these tests.

SECTION III

AVIATION FUELS JP4, JP5, AND JP8 VERSUS CD2022 PLUS ADDITIVES

A. INTRODUCTION

At the present time JP4 is used extensively in the United States Air Force not only as an aviation fuel but also for firefighter training. The US Navy uses primarily JP5 for its aviation and training applications. JP8 is already used for some Air Force applications and is slated as a replacement for JP4. Its civilian version (JET A) is used extensively in the airline industry. As discussed in section I, a new fuel designated CD2022, when mixed with the smoke reducing additive, has proved to yield superior emissions performance than these aviation fuels.

A series of 6 feet diameter fire tests were performed in which the relative emissions performance of the three aviation fuels and CD2022 with and without additive was compared and contrasted. These tests were performed in the Controlled Environment Burn Facility, described in section II. Ten gallons of fuel was used in each case. The results obtained are described below. These tests complement similar series of tests performed at the Canadian National Fire Laboratory in which 3 foot diameter fires were studied. These tests are described in references 5 and 6.

B. RESULTS

1. Soot Production

Figure 5 shows the relative soot masses collected on all the filters for the fuel and fuel/additive mixtures indicated. It is seen that JP5 yields the greatest amount of soot with JP8 being little better. It is clear that these two fuels are less desirable than JP4 for firefighter training purposes from an environmental standpoint. CD2022 on its own yields about a third the soot of JP4 but with the smoke reducing additive, very large reductions (up to 98%) in soot emission are seen. Table 10 lists the soot reductions of the various fuel and fuel/additive mixtures compared to JP4. The negative values for JP5 and JP8 indicate an enhancement of soot emission.

It is possible to obtain an estimate of the total percentage of the fuel converted to soot using the carbon balance method. This involves determining the masses of soot, CO and CO₂ collected and comparing them with the original mass of carbon in the fuel. Attempts were made to determine CO and CO₂ yields in the present measurements but the available gas analysis equipment proved too insensitive to yield accurate and meaningful results. Researchers elsewhere (Reference 7) have found that approximately 10% of hydrocarbon fuels such as JP4 are converted to soot and so we shall take this figure as being representative of these tests.

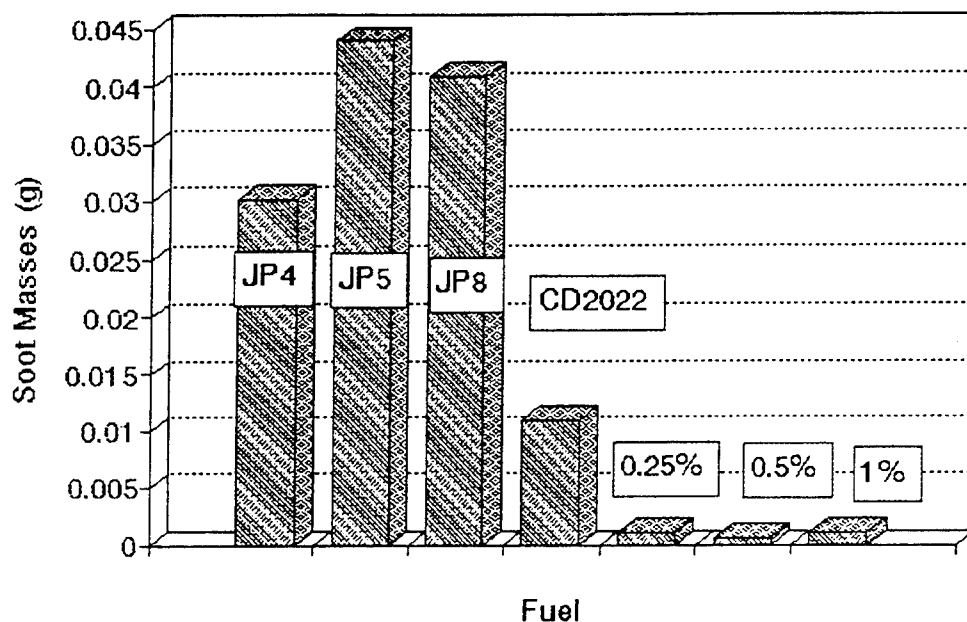


Figure 5. Soot masses collected from fires of JP4, JP5, JP8, CD2022 and CD2022 with indicated additive concentrations.

TABLE 10. SOOT EMISSION REDUCTIONS RELATIVE TO JP4

Fuel	Soot Mass Collected (grams)	Soot Mass Reduction (%)
JP4	0.0303	0
JP5	0.0439	-45
JP8	0.0409	-35
CD2022	0.0109	64
CD2022 + 1% Additive	0.0011	96
CD2022 + 0.5% Additive	0.0006	98
CD2022 + 0.25% Additive	0.0011	96

2. Smoke Opacity

Smoke opacity is the degree of obscuration of transmitted light by the plume arising from a fire and as described in section II this was determined using a laser/photodetector apparatus. Figures 6 and 7 show transmitted light traces taken during fires of JP4 and CD2022 plus 1.0% additive. (Note the difference in scales). It is seen that there is drifting of the signal in the latter case so that the initial and final measured powers are not the same. This was a frequent problem during these tests and meant that good data was only obtained in limited cases. The drifting is most likely due to misalignment of the optical system occurring during the burn. Clearly there is a need for a more satisfactory method of mounting the laser and photodetector to achieve a more consistent success rate. Figure 8 shows relative values of light absorption for JP4 and CD2022 with 0.25%, 0.5% and 1% additive. Table 11 shows the reductions in opacity obtained for the CD2022 plus additive fuel mixtures compared to JP4. It is seen that reductions of between 80% and 85% are obtained with the new fuel/additive mixture.

These reductions are not as great as the reductions observed in collected soot masses. The fact is that smoke is very effective in causing light obscuration and even the small amount produced with the CD2022/Additive mixtures is sufficient to block at least some of the incident light. This has a direct consequence when the fire size is scaled up for even though there is a dramatic reduction in soot mass, the smoke plume is still very visible. This was noticed in the large-scale fires described in section VI.

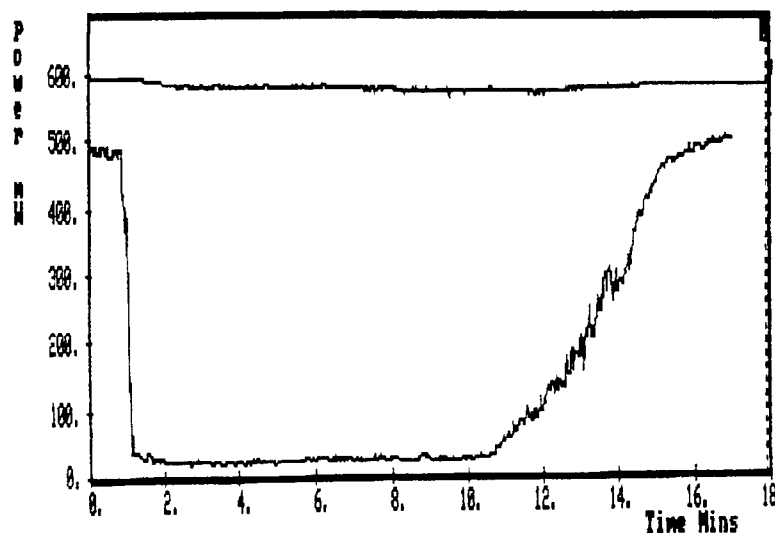


Figure 6. Transmitted light measured during fires of JP4 (bottom trace) and CD2022 + 1% additive (top trace).

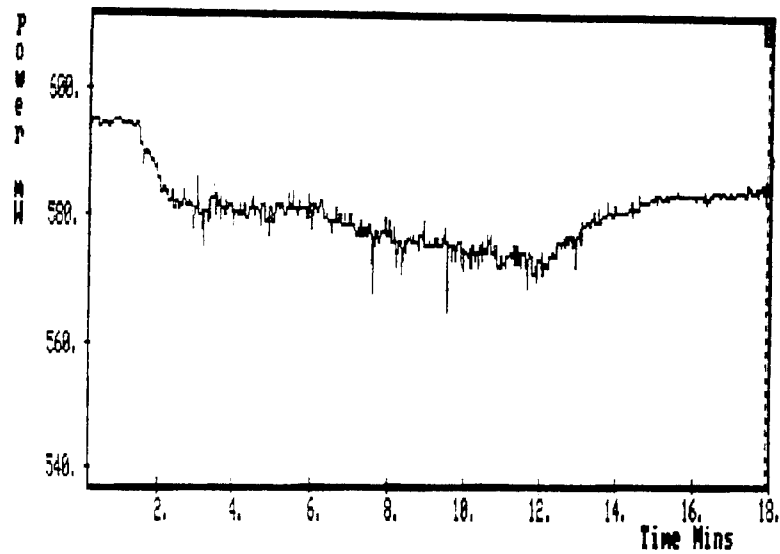


Figure 7. Transmitted light measured during a fire of CD2022 + 1% additive shown on an expanded scale.

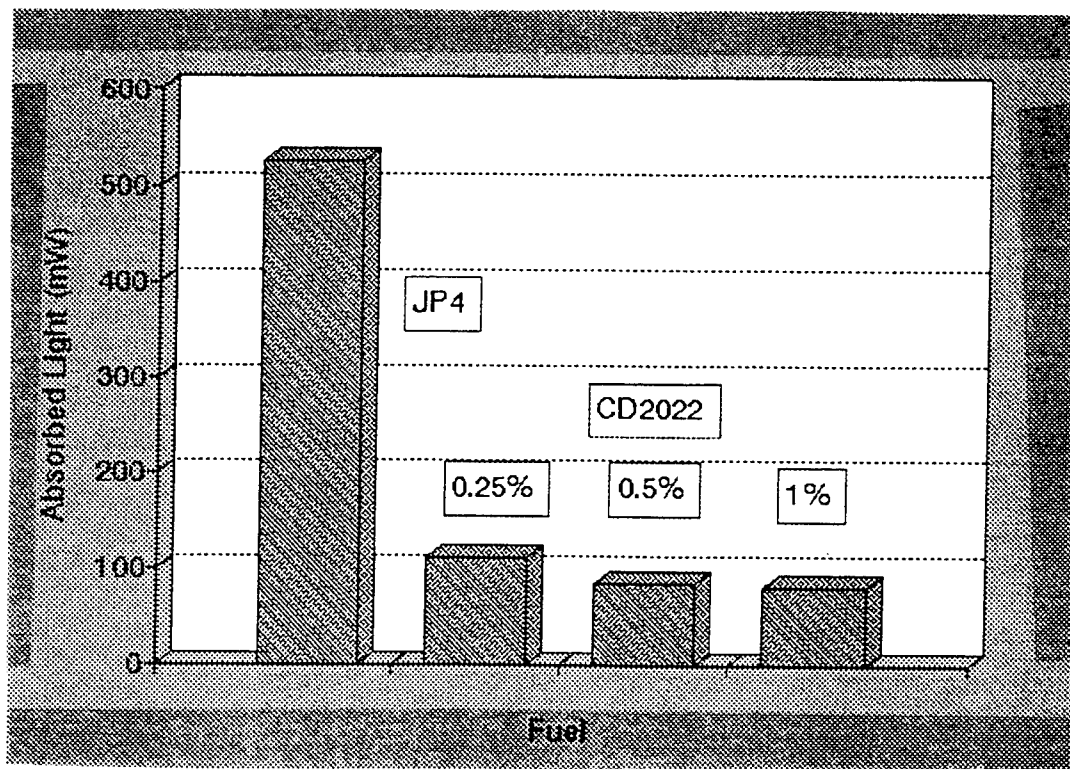


Figure 8. Absorption of laser light for JP4 as compared to CD2022 with indicated additive concentrations.

TABLE 11. OPACITY REDUCTIONS COMPARED TO JP4

Fuel	Opacity Reduction (%)
JP4	0
CD2022 + 0.25% Additive	79%
CD2022 + 0.5% Additive	84%
CD2022 + 1.0% Additive	85%

3. Flame Temperatures

Flame temperatures measured using the thermocouple array described in section II are shown for JP4, JP5 and JP8 in figures 9-11 and for CD2022 with varying additive concentrations in figures 12-15. It is seen that JP4 yields maximum temperatures somewhat higher than for JP5, JP8 and for the CD2022 fuel/additive mixtures. It would also appear that JP4 maintains its maximum temperature more consistently during the burn. The CD2022/additive show temperatures rapidly rising to a maximum value and followed by a steady fall off.

4. Volatile Organic Carbon Emissions

The main VOC's detected from these tests were benzene and toluene, all other compounds being below detectable limits. Figures 16 and 17 show the relative concentrations of benzene and toluene for JP4 and for CD2022 with 0.25%, 0.5% and 1% Additive added. It is clear that use of the new fuel/additive mixture results in large reductions in the emission of benzene and toluene. The exact reductions are listed in Table 12.

5. Polycyclic Aromatic Hydrocarbon (PAH) Emissions

Three volatile polycyclic aromatic hydrocarbon species were detected from analysis of the Tenax sorbent tubes and these were identified as naphthalene, acenaphthylene and 1,1-biphenyl. The relative measured concentrations of these species are shown in figures 18 and 19. When CD2022 + Additive is used, large reductions are seen for these three compounds compared with JP4. The reductions are listed in table 13.

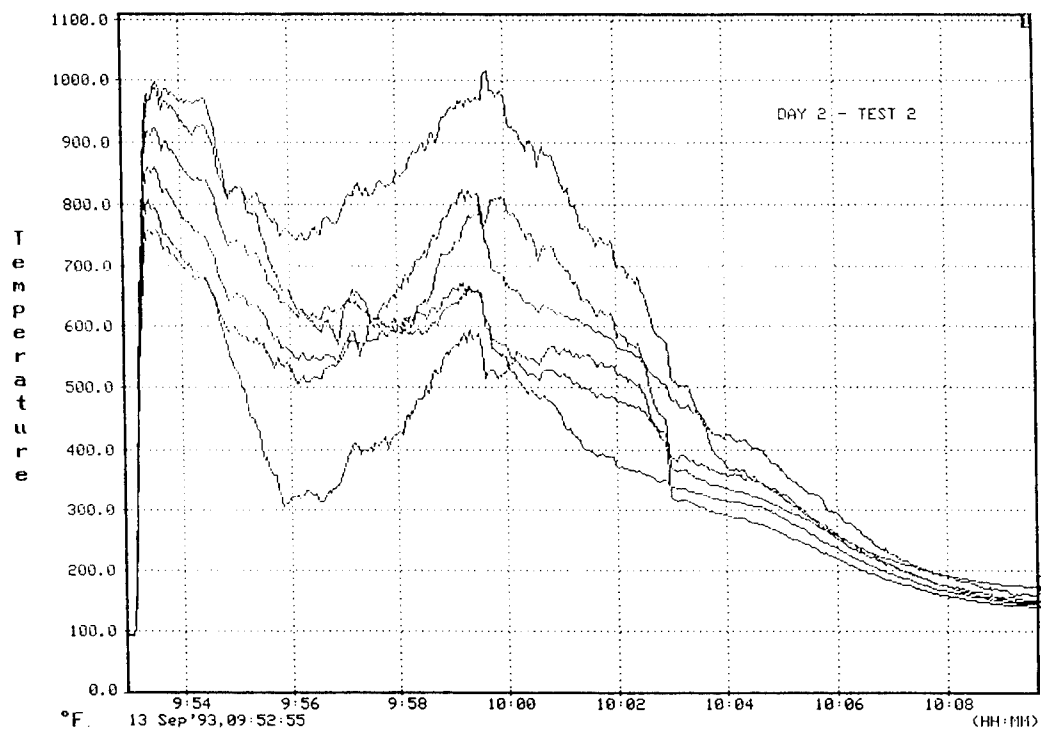


Figure 9. Flame temperature profile for JP4.

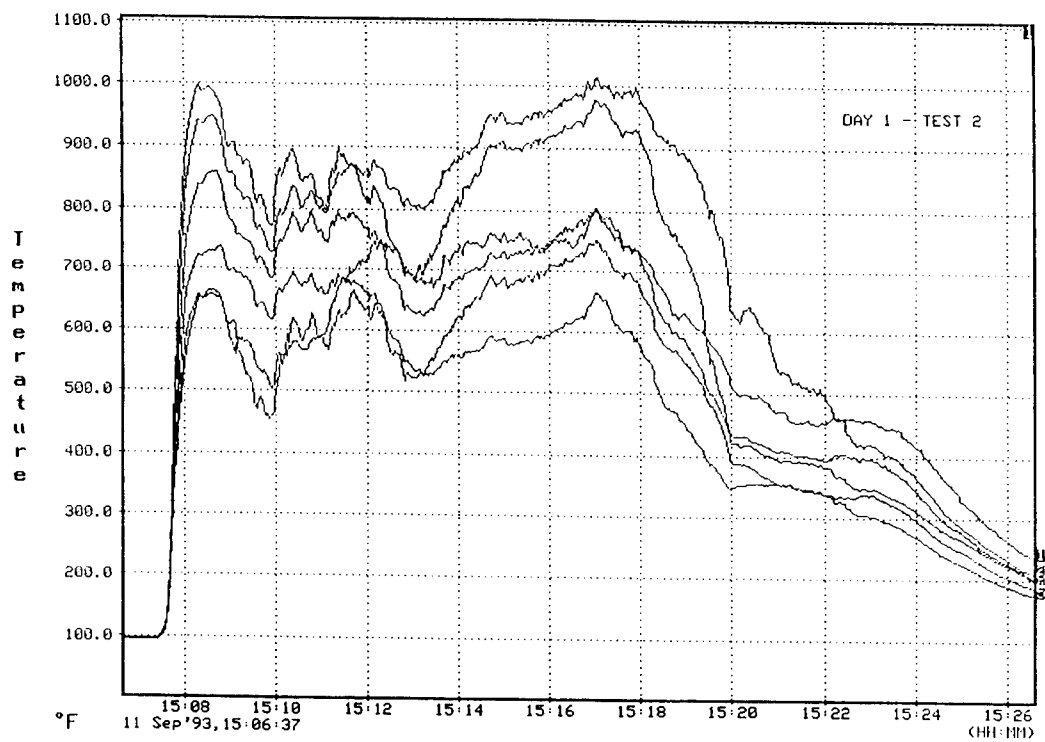


Figure 10. Flame temperature profile for JP5.

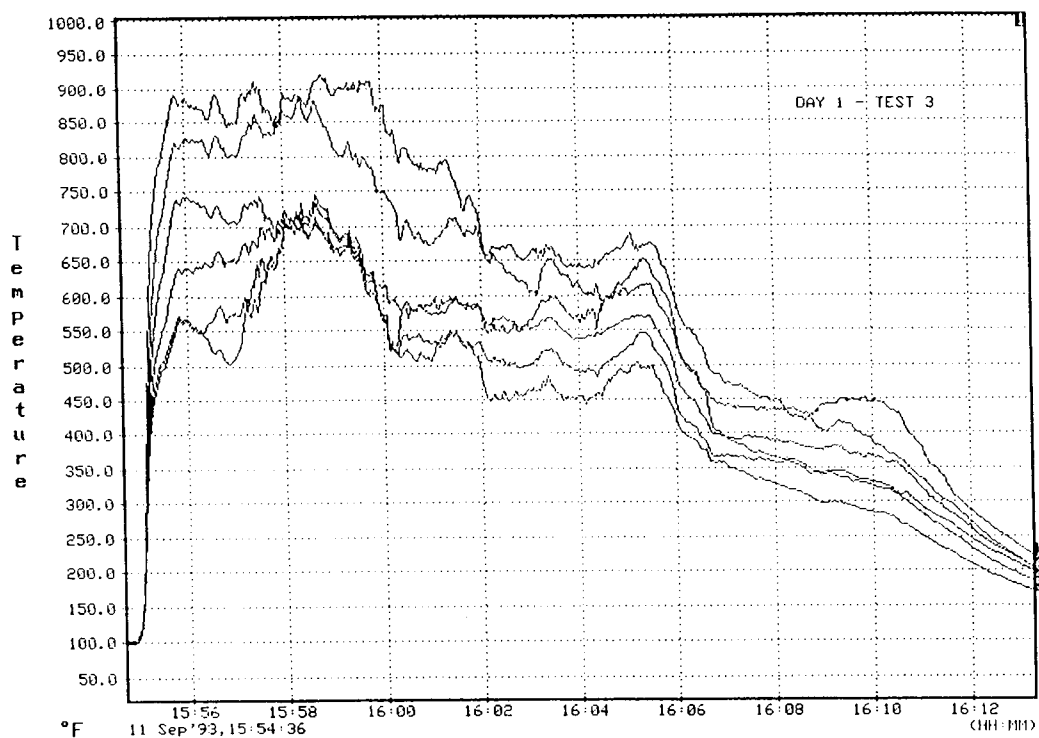


Figure 11. Flame temperature profile for JP8.

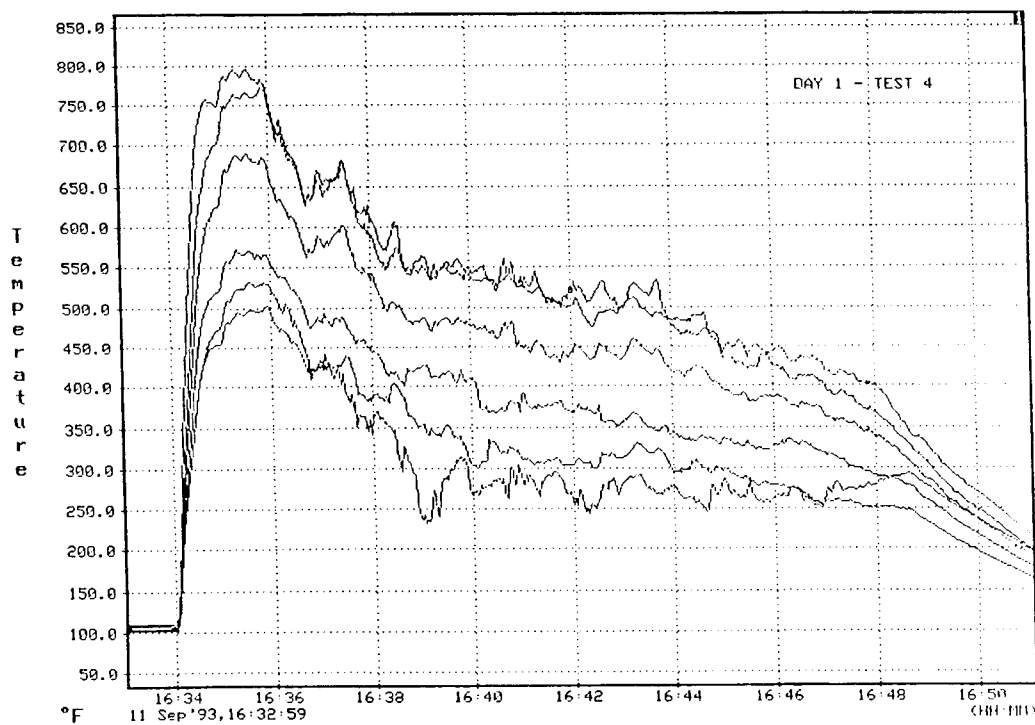


Figure 12. Flame temperature profile for CD2022.

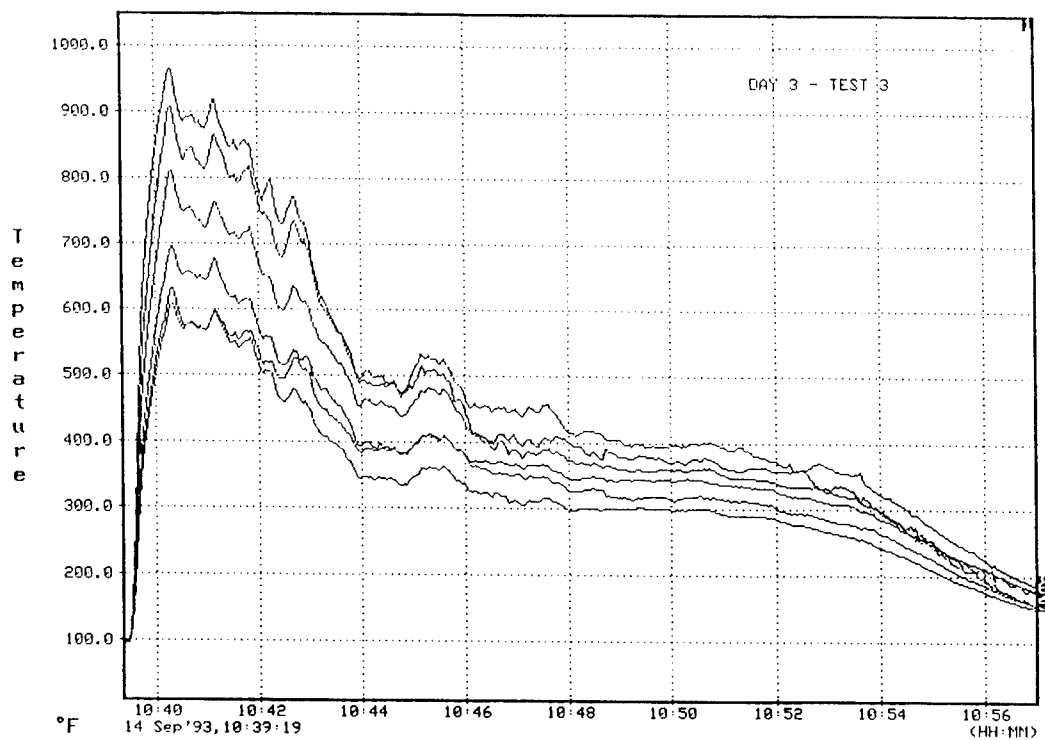


Figure 13. Flame temperature profile for CD2022 + 0.25% additive.

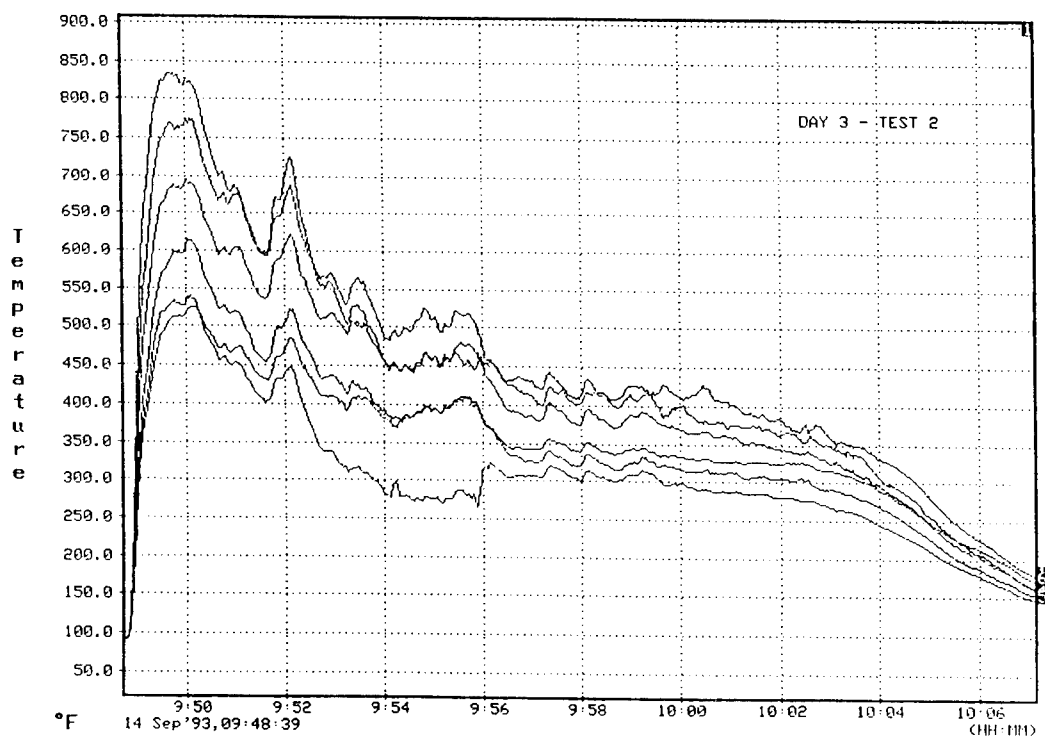


Figure 14. Flame temperature profile for CD2022 + 0.5% additive.

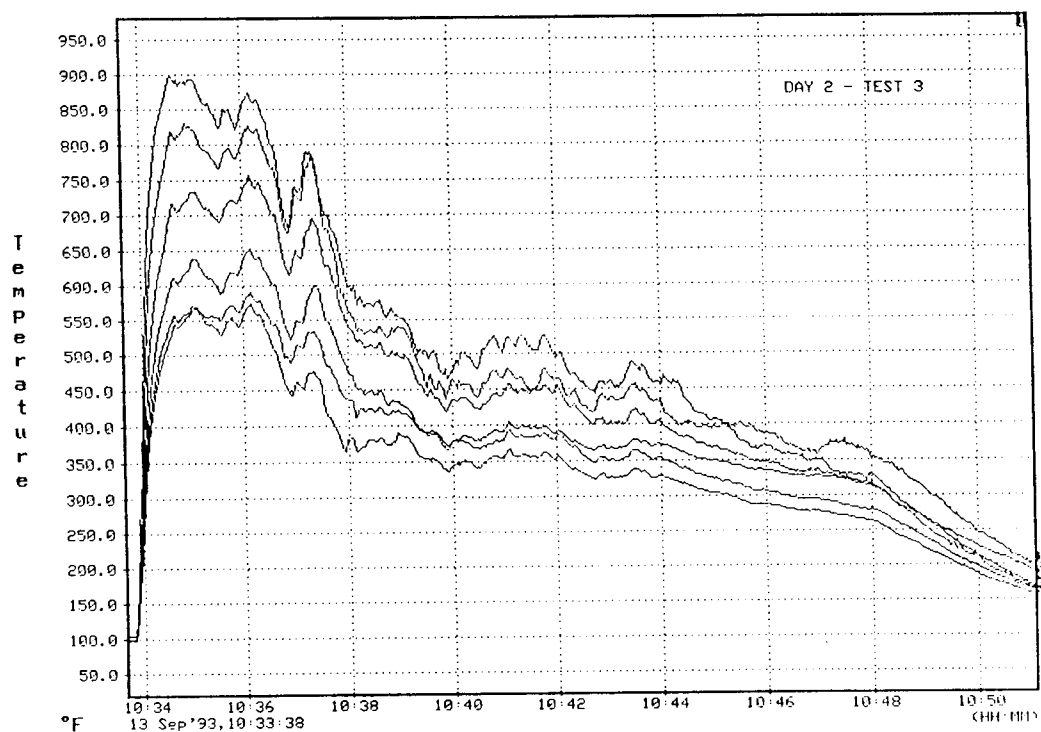


Figure 15. Flame temperature profile for CD2022 + 1.0% additive.

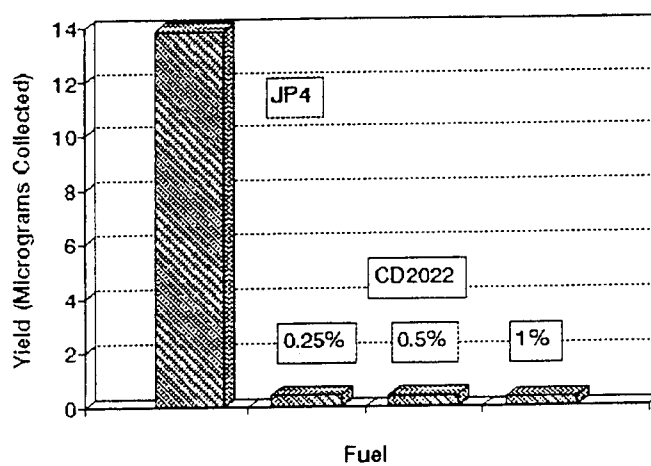


Figure 16. Relative collected masses of benzene from fires of JP4 and CD2022 with indicated additive concentrations.

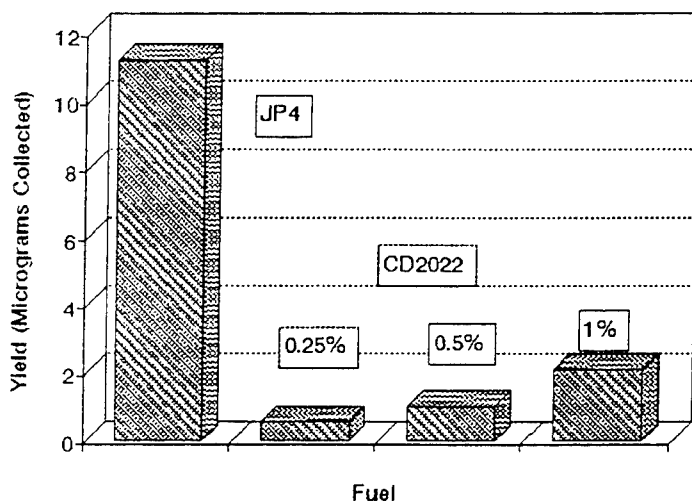


Figure 17. Relative collected masses of toluene from fires of JP4 and CD2022 with indicated additive concentrations.

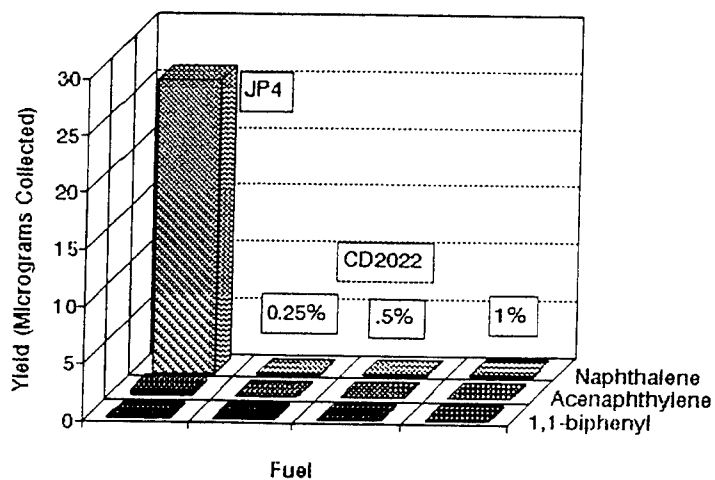


Figure 18. Relative collected masses of volatile PAH's from fires of JP4 and CD2022 with indicated additive concentrations.

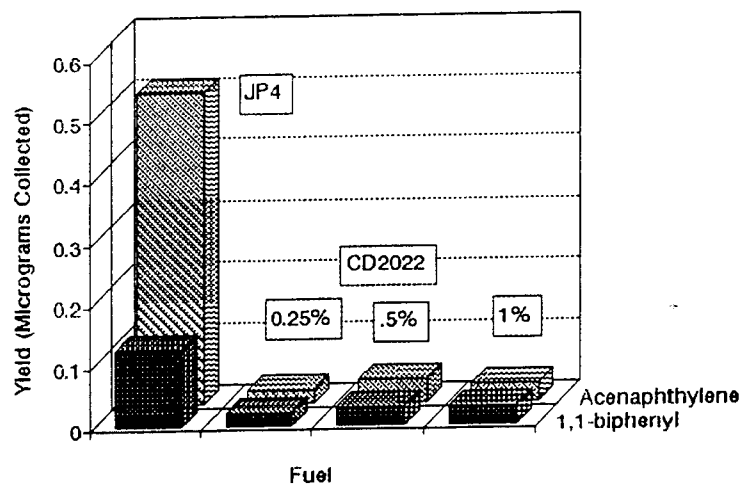


Figure 19. Relative collected masses of acenaphthylene and 1,1-biphenyl from fires of JP4 and CD2022 with indicated additive concentrations.

TABLE 12. REDUCTIONS IN BENZENE AND TOLUENE EMISSIONS COMPARED TO JP4

FUEL	Benzene Reduction	Toluene Reduction
JP4	0%	0%
CD2022 + 0.25%	97%	95%
CD2022 + 0.5%	97%	91%
CD2022 + 1%	98%	81%

TABLE 13. REDUCTIONS IN THE EMISSIONS OF VOLATILE PAH'S COMPARED TO JP4

FUEL	Naphthalene Reduction	Acenaphthylene Reduction	1,1-biphenyl Reduction
JP4	0%	0%	0%
CD2022 + 0.25%	99.7%	95.8%	82.6%
CD2022 + 0.5%	99.7%	92.6%	76.1%
CD2022 + 1%	99.6%	94.2%	76.1%

Figure 20 shows the relative concentrations of PAH's recovered using soxhlet extraction of the soot samples collected on the filters during fires of JP4 and CD2022 with and without additive. The individual PAH's can be identified with the aid of Table 9. (Although detected as a component of the soot, naphthalene is not included in this list because its volatility make its collection in the soot matrix and subsequent extraction very uncertain). It is clear that the CD2022 plus additive fuels give greatly reduced yields of non-volatile PAH's compared to JP4. The amounts of these reductions compared to JP4 are listed in Table 14.

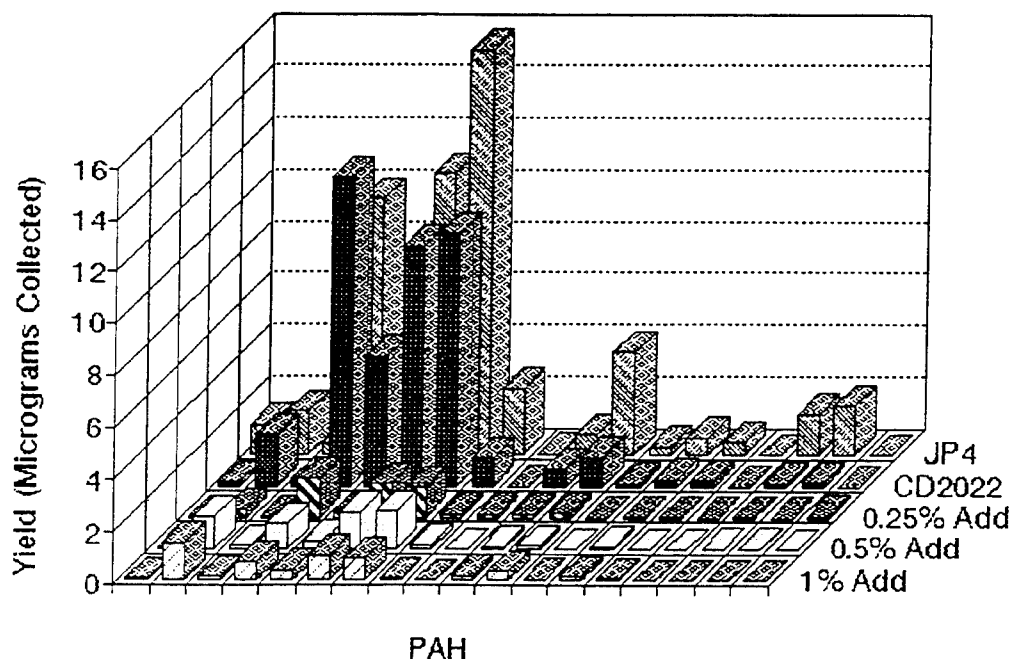


Figure 20. Relative collected masses of non-volatile PAH's from fires of JP4 and CD2022 with indicated additive concentrations.

TABLE 14. PERCENTAGE REDUCTIONS IN NON-VOLATILE PAH EMISSIONS COMPARED TO JP4

FUEL	Phenanthrene	Fluoranthene	Pyrene	Total PAH
JP4	0%	0%	0%	0%
CD2022	-21%	15%	37%	22%
CD2022 + 0.25% Additive	85%	88%	93%	91%
CD2022 + 0.5% Additive	90%	87%	91%	89%
CD2022 + 1% Additive	93%	92%	95%	91%

Figures 21-23 show measured concentrations of three of the most abundant PAH's; phenanthrene, fluoranthene and pyrene for the JP4 and CD2022 fuels. It is seen from Table 14 that in each case the use of the smoke reducing additive gives great reductions in the emissions of these compounds. Most PAH's have been recognized as carcinogens or potential carcinogens so these reductions are very significant.

Figure 24 shows the relative concentrations of the measured PAH's for the three commonly used jet fuels, JP4, JP5 and JP8. It is seen that of the three, JP4 is in fact the cleanest. JP5 is found to yield 51% more PAH's than JP4. JP8 yields 34% more. Figures 25-27 show relative concentrations of phenanthrene, fluoranthene and pyrene for these fuels. Also shown for comparison is the yield for CD2022 + 0.5% additive.

6. Aldehyde Emissions

Figures 28 and 29 show the measured concentrations of formaldehyde and propionaldehyde emitted during fires of JP4, neat CD2022 and CD2022 with varying concentrations of additive. It can be seen that formaldehyde emissions are reduced for the CD2022 cases with respect to JP4, the reductions being listed in Table 15.

The CD2022 fuel cases clearly show much less formaldehyde emission compared to JP4, and it would appear that the additive leads to some further improvement. The trend to increasing formaldehyde yield with increasing additive concentration is somewhat surprising but can most likely be attributed to scatter in the results. Experience has shown that our method for aldehyde measurements is subject to considerable uncertainty and can only be relied upon to give a indications of gross changes. This is seen in figure 31 where there is considerable scatter in the results for propionaldehyde emission. Very little consistent difference can be seen between JP4 and the CD2022/additive fuels.

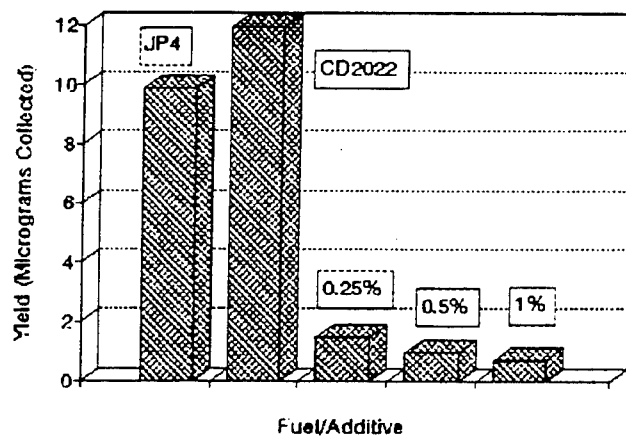


Figure 21. Measured phenanthrene concentrations.

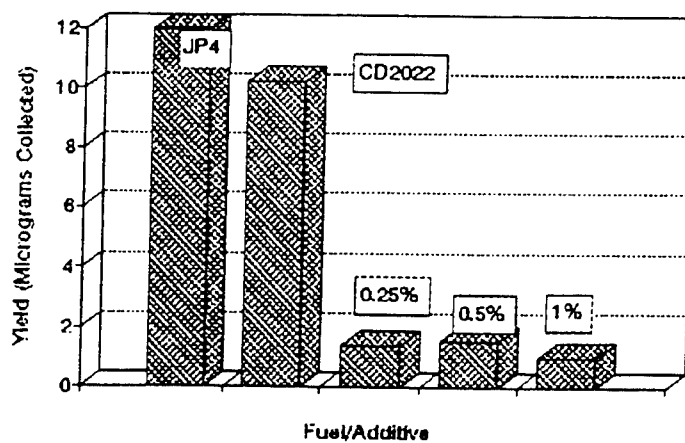


Figure 22. Measured fluoranthene concentrations.

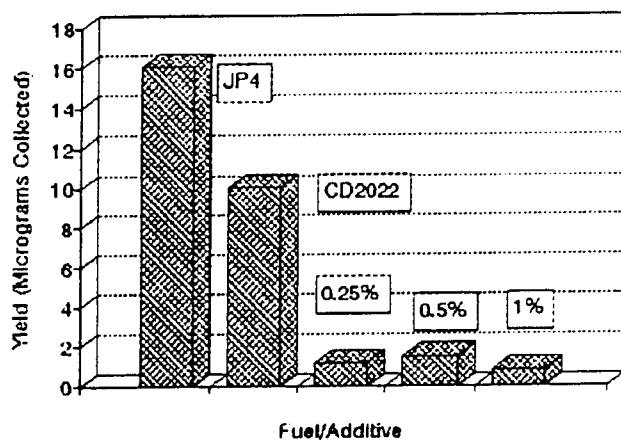


Figure 23. Measured pyrene concentrations.

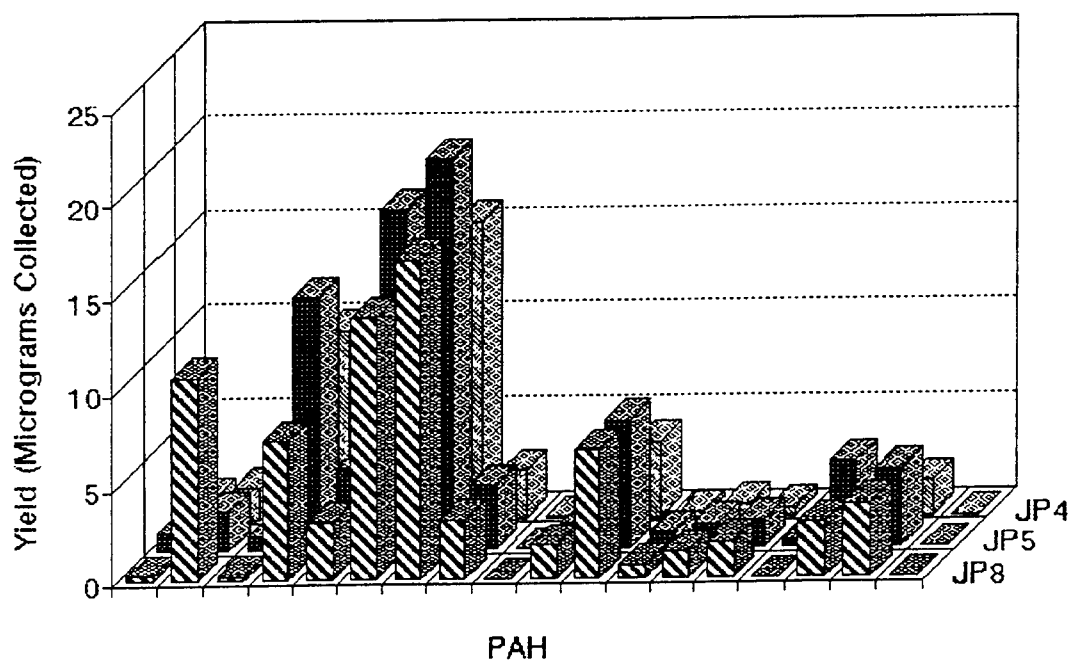


Figure 24. Relative collected masses of non-volatile PAH's from fires of JP4, JP5 and JP8 (see Table 9 for legend).

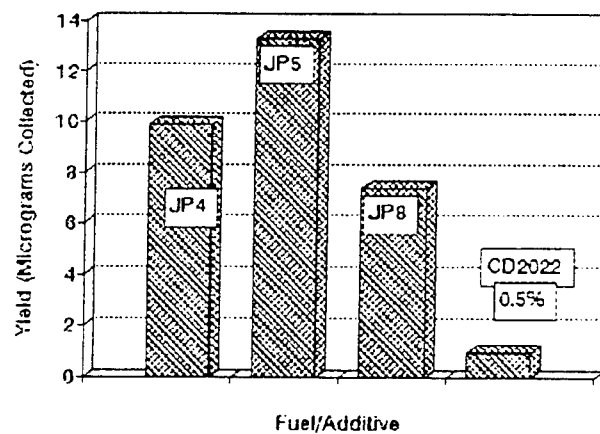


Figure 25. Measured phenanthrene concentrations.

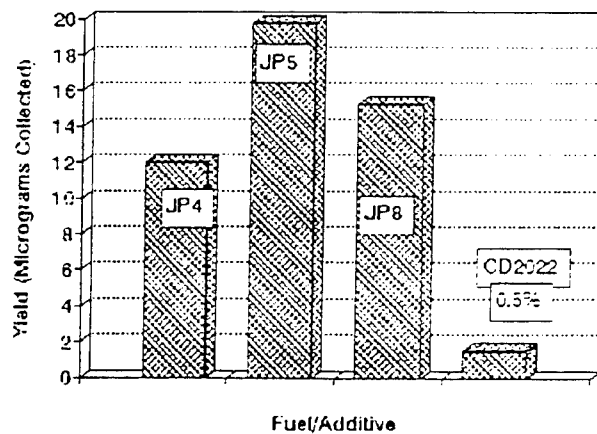


Figure 26. Measured fluoranthene concentrations.

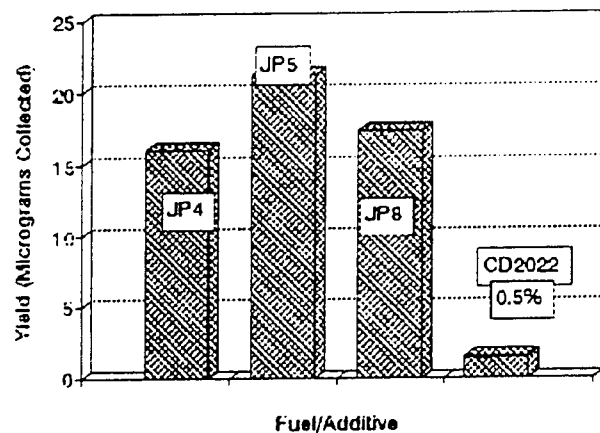


Figure 27. Measured pyrene concentrations.

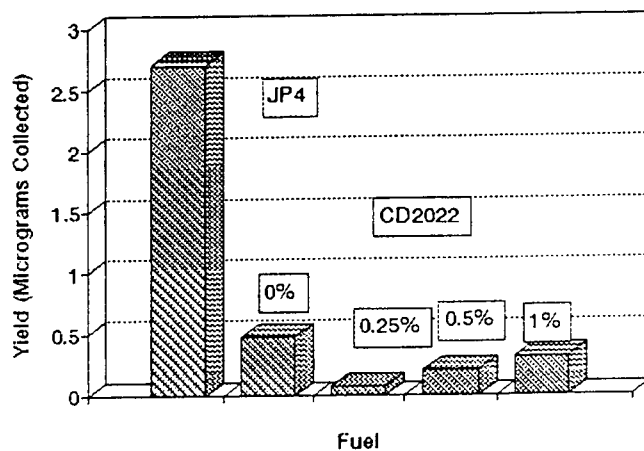


Figure 28. Formaldehyde emissions.

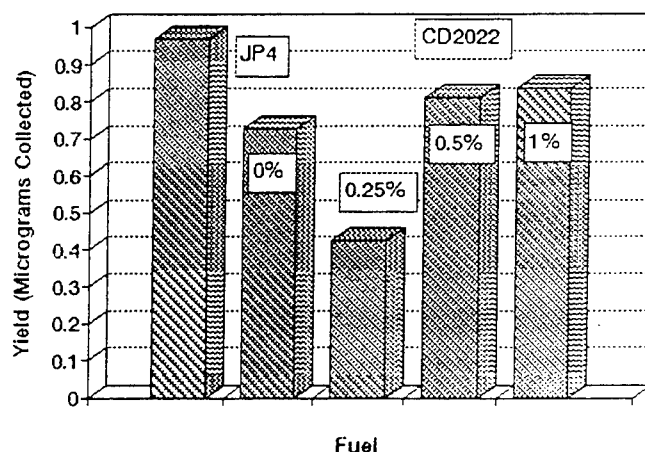


Figure 29. Propionaldehyde emissions.

TABLE 15. PERCENTAGE REDUCTIONS IN FORMALDEHYDE COMPARED TO JP4

Fuel	Formaldehyde Reduction (%)
JP4	0
CD2022	83
CD2022 + 0.25% Additive	97
CD2022 + 0.5% Additive	93
CD2022 + 1% Additive	89

Figures 30 and 31 show the relative concentrations of formaldehyde and propionaldehyde emitted for the jet fuels JP4, JP5 and JP8 along with that for CD2022 + 0.5% additive for comparison. JP5 and JP8 show surprisingly low concentrations of formaldehyde compared with JP4 (80% and 90% less respectively). For propionaldehyde, the results are rather inconclusive.

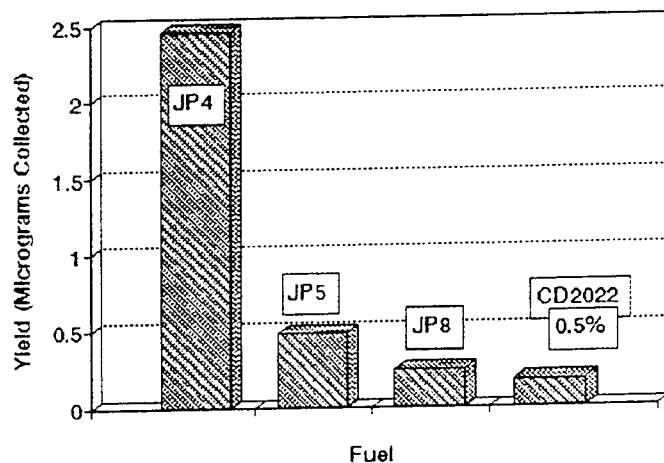


Figure 30. Relative collected masses of formaldehyde from fires of JP4, JP5 and JP8.

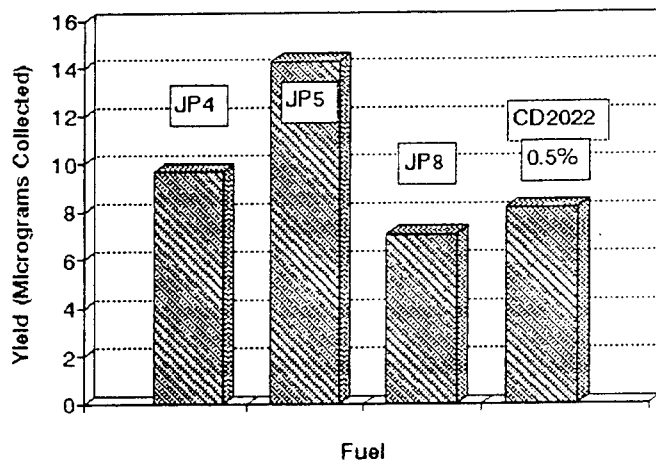


Figure 31. Relative collected masses of propionaldehyde from fires of JP4, JP5 and JP8.

SECTION IV

JP4 PLUS ADDITIVE

A. INTRODUCTION

In the previous report on the Clean Air Firefighting project (Reference 4) the use of various smoke reducing additive mixtures with JP4 was described. It was found that when used at concentrations up to 6%, these additive mixtures reduced the amount of soot produced from JP4 by up to 80%. An economic analysis however, indicated that the derivatives were very expensive to procure. In addition, large scale testing conducted at the Sarnia Industrial Fire School in Canada indicated that the smoke output was unacceptable. This was the reason that a cleaner fuel such as CD2022, mixed with a smoke reducing additive, was tried. For completeness, it was decided that two tests involving the use of the additive with JP4 should be conducted so that the results could be compared directly with those for the CD2022 plus additive tests. These tests used 0.5% and 1% additive respectively and the results are presented below.

B. RESULTS

1. Soot Masses

Total soot masses collected on the various filters, compared with that for neat JP4 are shown in figure 32. Also shown is the soot mass collected from using CD2022 plus 0.5% additive for comparison. It is seen that the latter fuel performs much better than the JP4 plus additive although the JP4/additive mixtures do produce an 80% reduction in soot mass.

2. Opacity

These tests were performed during a period when the opacity apparatus was not performing optimally and reliable data was not obtained.

3. Flame Temperatures

Flame temperatures measured during these tests are shown in figure 33-35. It is seen that there is little or no difference between the neat fuel and the fuel plus additive cases.

4. Volatile Organic Carbons (VOC's)

Again, benzene and toluene were the only two VOC compounds identified that yielded measured concentrations above detectable limits. Figures 36 and 37 show their relative measured concentrations for neat JP4, and JP4 with 0.5% and 1% additive added. It is seen that the addition of additive leads to 90% reductions in the emission of benzene and about 65% reduction in the emission of toluene.

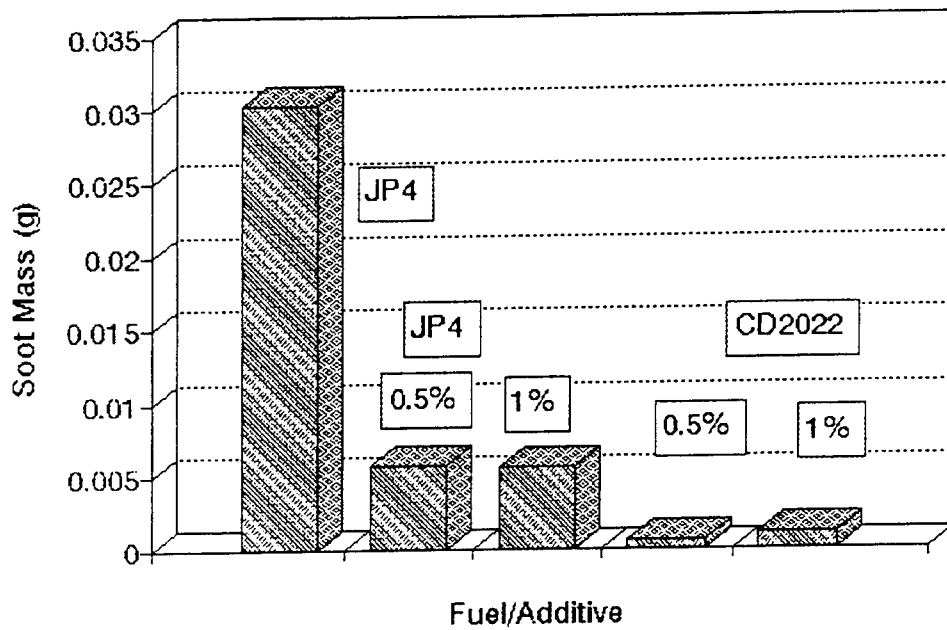


Figure 32. Relative soot masses collected from fires of JP4 and JP4 with indicated additive concentrations.

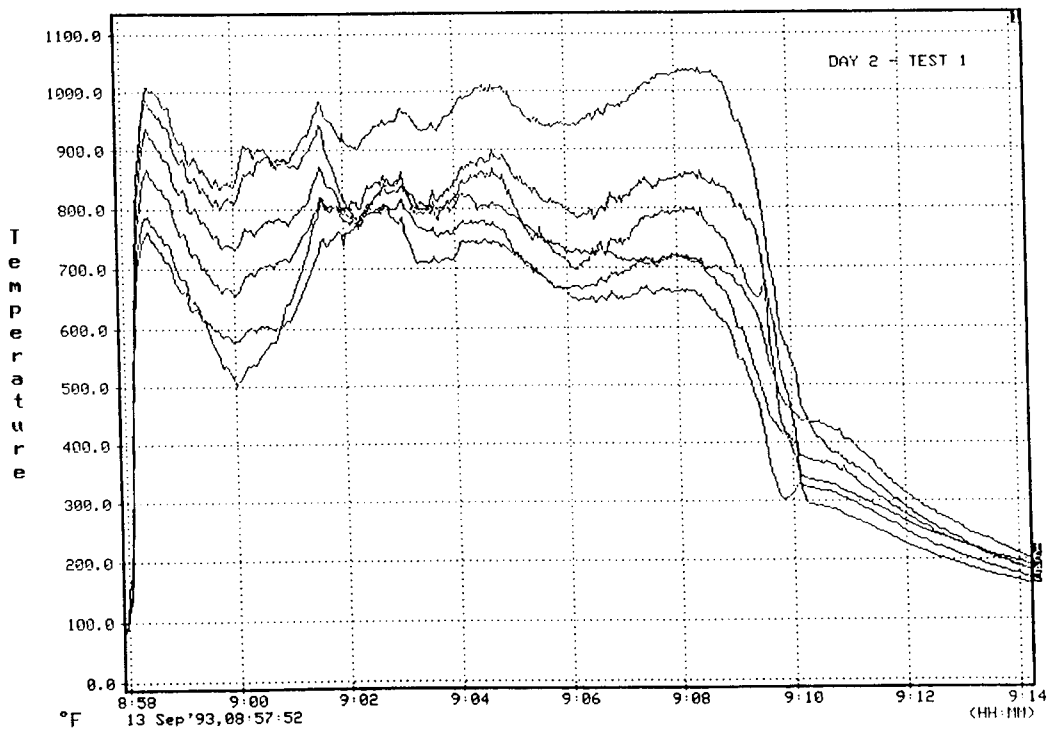


Figure 33. Flame temperature profile for JP4.

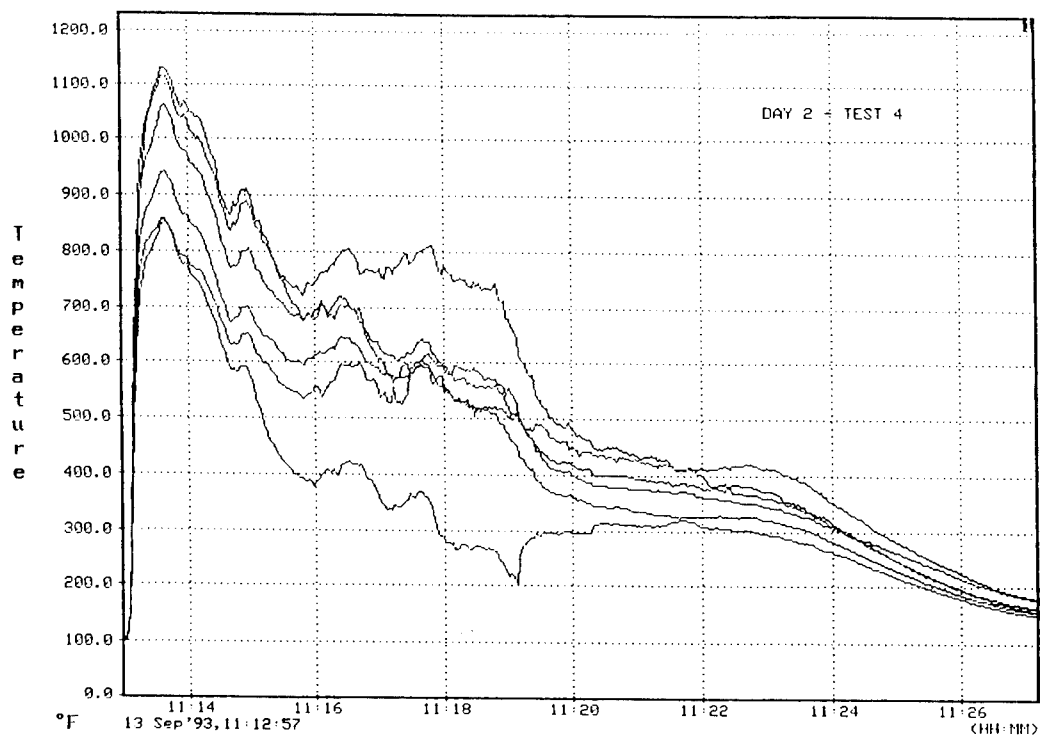


Figure 34. Flame temperature profile for JP4 + 0.5% additive.

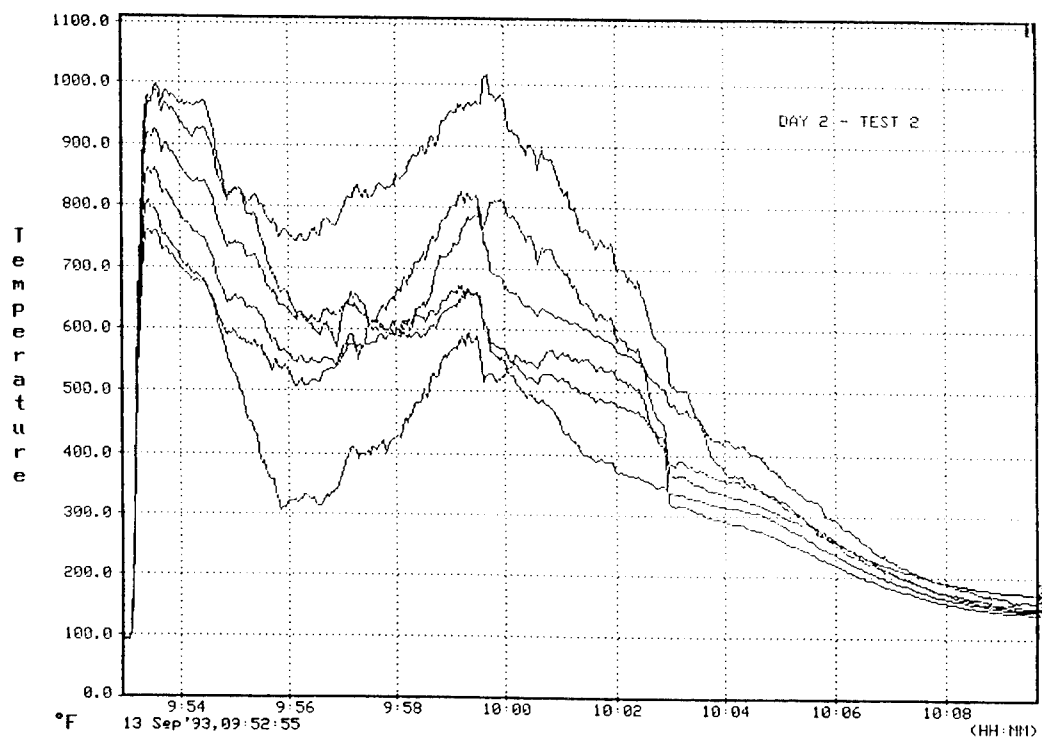


Figure 35. Flame temperature profile for JP4 + 1.0% additive.

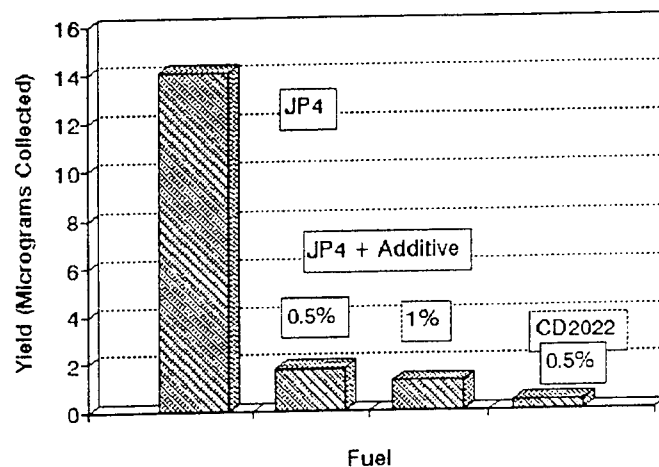


Figure 36. Relative collected masses of benzene from fires of JP4 and JP4 plus additive.

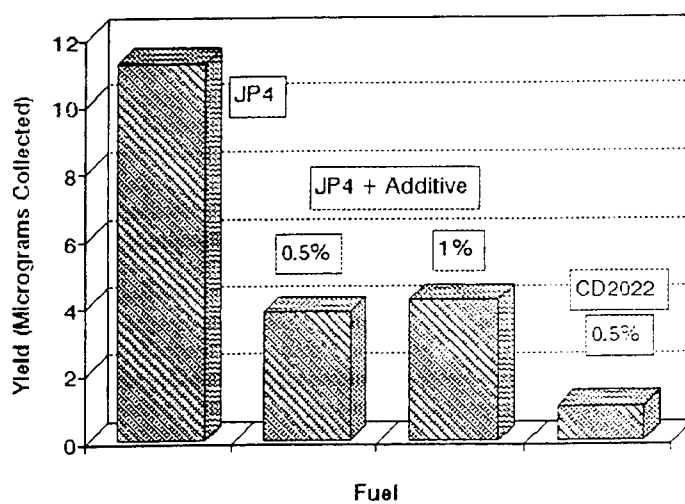


Figure 37. Relative collected masses of toluene from fires of JP4 and JP4 plus additive.

5. Polycyclic Aromatic Hydrocarbons (PAH's)

Figures 38 and 39 show the relative concentrations of three volatile PAH's detected from analysis of the Tenax sorbent tubes. It is clear from Table 16 that the additive is very effective in reducing the concentrations of these species.

TABLE 16. REDUCTIONS IN VOLATILE PAH EMISSION COMPARED TO JP4

FUEL	Naphthalene	Acenaphthylene	1,1-biphenyl
JP4	0%	0%	0%
JP4 + 0.5% Add	88%	81%	55%
JP4 + 1% Add	96%	83%	59%
CD2022 + 0.5% Add	99.7%	92.6%	76.1%

The non-volatile PAH's are shown in figure 40 however and here it is seen that the additive is less effective. Reductions are seen but amount to only 32% and 52% respectively. Figures 41-43 show the relative concentrations of three of the more abundant PAH's; phenanthrene, fluoranthene and pyrene. Also shown in the figures are concentrations of these compounds detected in soot from a fire of CD2022 + 0.5% additive. It is seen that the latter fuel gives much smaller yields of these compounds. This shows that in order to obtain clean burning fires it is essential to start with a relatively clean fuel such as CD2022 and then to use the additive to produce further reductions in toxics. Table 17 lists the reductions in non-volatile PAH's compared to JP4.

TABLE 17. REDUCTIONS IN NON-VOLATILE PAH EMISSION COMPARED TO JP4

FUEL	Phenanthrene Reduction	Fluoranthene Reduction	Pyrene Reduction	Total PAH
JP4	0%	0%	0%	0%
JP4 + 0.5% Add	14%	24%	50%	32%
JP4 + 1% Add	40%	47%	62%	52%
CD2022 + 0.5% Add	90%	87%	91%	89%

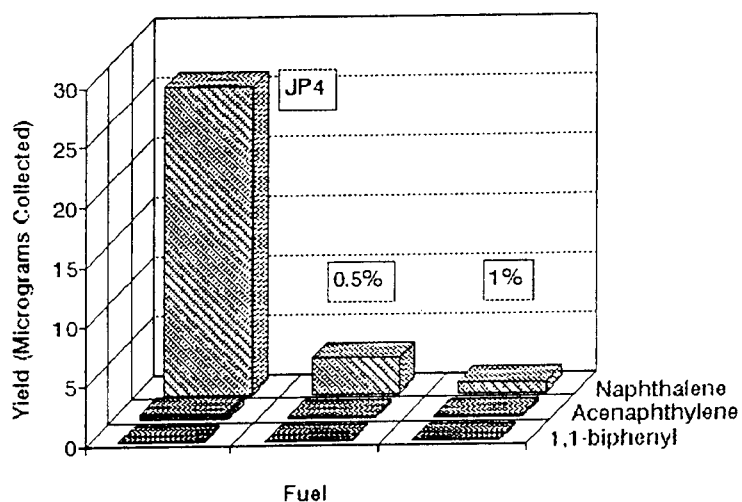


Figure 38. Relative collected masses of volatile PAH's from fires of JP4 and JP4 plus additive.

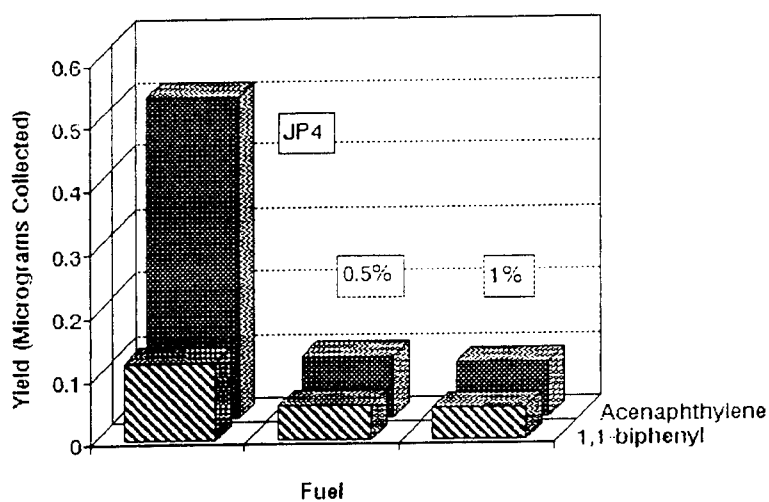


Figure 39. Relative collected masses of acenaphthylene and 1,1-biphenyl from fires of JP4 and JP4 plus additive.

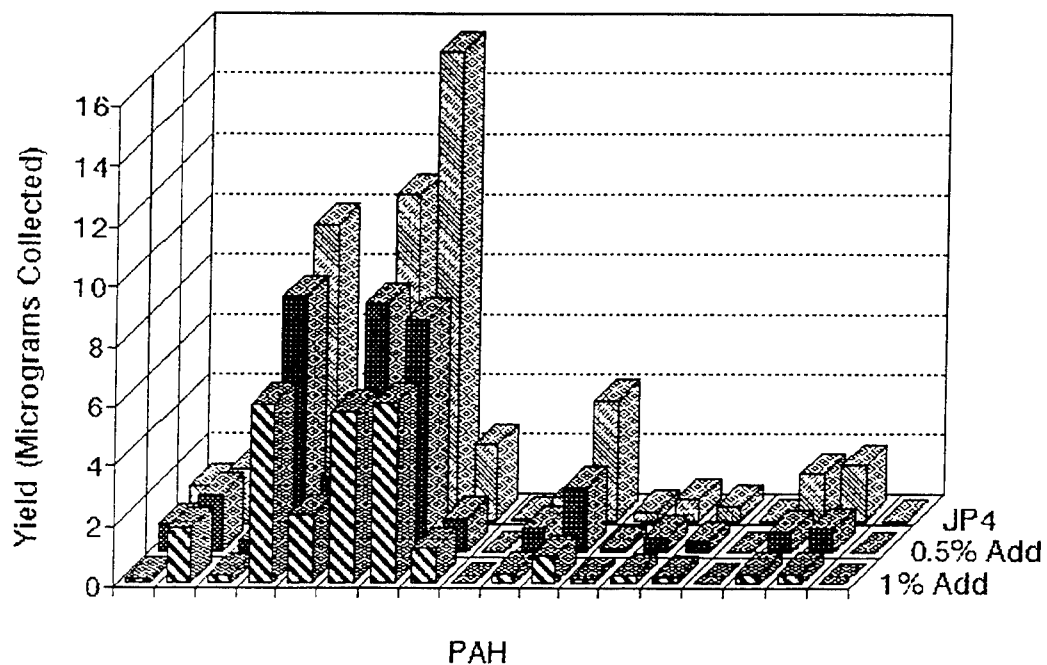


Figure 40. Relative collected masses of non-volatile PAH's from fires of JP4 and JP4 plus additive (see Table 9 for legend).

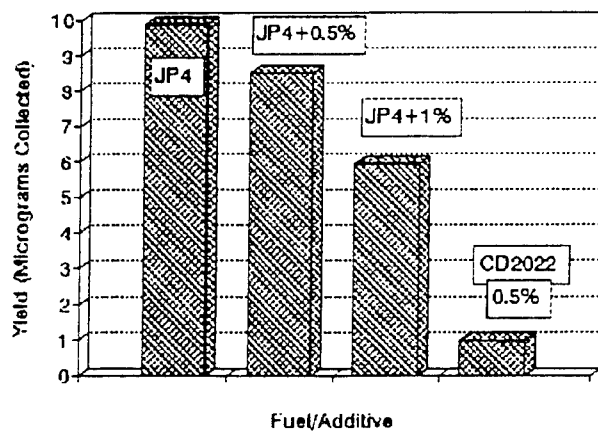


Figure 41. Relative concentration of phenanthrene.

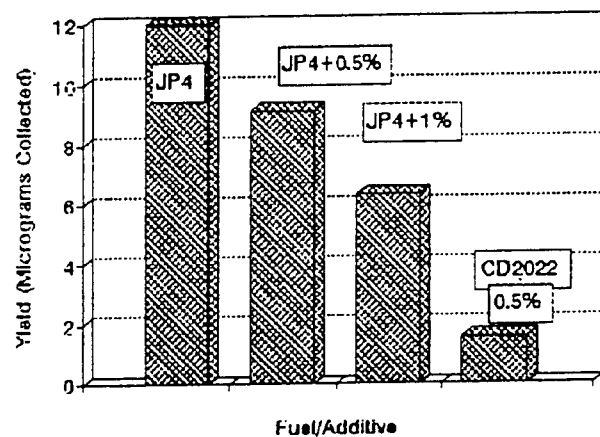


Figure 42. Relative concentration of fluoranthrene.

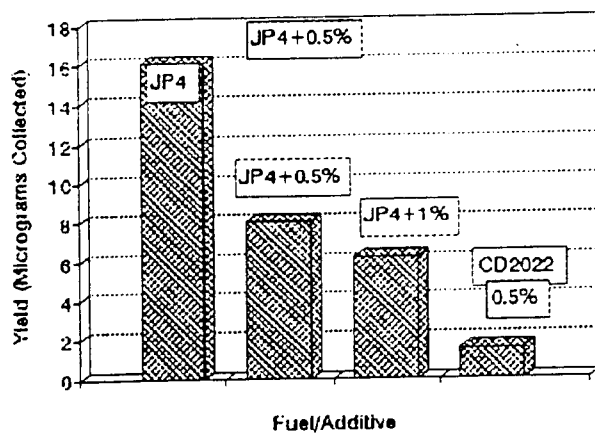


Figure 43. Relative concentration of pyrene.

6. Aldehydes

Figures 44 and 45 show the emissions of formaldehyde and propionaldehyde from these fires. It is seen that the use of additive leads to a 66% reduction in the emission of formaldehyde but again the propionaldehyde data is ambiguous. It would seem that there is little or no effect on the emission of this compound.

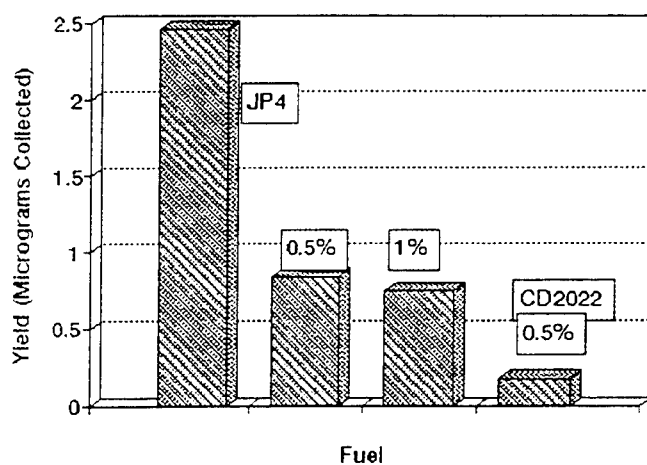


Figure 44. Relative collected masses of formaldehyde from fires of JP4 and JP4 plus additive.

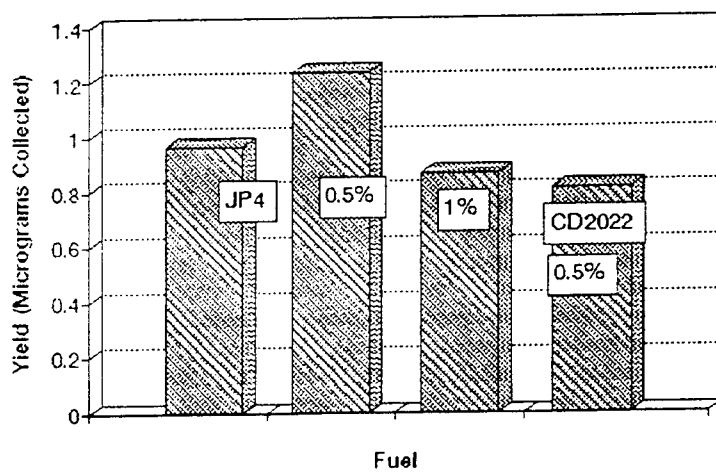


Figure 45. Relative collected masses of propionaldehyde from fires of JP4 and JP4 plus additive.

SECTION V

EMISSIONS FROM THE USE OF FIREFIGHTING AGENTS

A. INTRODUCTION

The work described up to now in this report deals with the emissions from fires, of various fuels that were allowed to burn out without external intervention. In practice of course, during the course of fire training exercises, the fires will be attacked by firefighting agents such as water, Aqueous Film Forming Foam (AFFF), Dry Chemical or Halon 1211. These agents themselves can of course affect the emissions from the fires and in some case add new agents due to decomposition products. Very little information is available concerning the effects of these agents and so this has been addressed in the following section. Tests were performed in which the agents AFFF, Dry Chemical and Halon 1211 were introduced into the fires at a rate insufficient to cause extinguishment. The sampling apparatus was operated as before and the emissions characterized. These agents are treated individually below.

B. AQUEOUS FILM FORMING FOAM (AFFF)

This product is widely used by airport firefighting departments and extensive large scale training is performed using it. A variety of foams are commercially available, the AFFF variety consisting of a fluorinated long-chain hydrocarbon compound that is mixed at a concentration of 3% in water before being delivered to the fire. These tests were performed on fires of JP4, and CD2022 with 0.25%, 0.5% and 1% additive. Eight liters of agent were sprayed onto the fires after they had been burning for a few minutes.

1. Soot Masses

Figure 46 shows the soot masses collected during the fires of JP4 and CD2022 plus 0.25%, 0.5% and 1% additive, with and without the injection of AFFF. Overall the introduction of the agent produces very little effect on the total soot production.

2. Opacity

Figure 47 shows the effect on the measured opacity of AFFF being introduced into the JP4 fire. This gives rise to the peak that is seen about 2 minutes after the beginning of the fire. This is correlated with the reduction of the fire size as seen by the flame temperature measurements discussed below and by video recording of the fire.

3. Flame Temperatures

The effect of the agent on fire temperatures can be seen in figures 48-51. It is seen that in each case the agent produced a decrease of about 600C in the measured temperatures and that this decrease lasted for a period of about 2 minutes, roughly the time for the application. After

each application, the measured temperatures returned to a level about 300C lower than the temperature measured at the beginning of the application.

4. Volatile Organic Carbon's (VOC's)

Figures 52 and 53 shows the relative amounts of benzene and toluene released during the JP4 and CD2022/additive fires with and without AFFF being introduced. What is rather surprising is the large reduction in benzene and toluene emission (90% and 83% respectively) seen for JP4. The effect is less noticeable for the CD2022 plus additive mixtures for there, the emissions are very small anyway.

In addition to these chemicals, a number of other peaks in the chromatograms were seen and these have been identified as being due to unburned fuel. These observations can probably be related to the sharp drop in temperature observed when the agent is applied. In figures 10 and 22 it is seen that the maximum temperature for JP4 fires is maintained throughout the burn while CD2022/additive fires seem to reach a maximum temperature and then cool off. In figure 48 it can be seen that the application of the AFFF results in a temperature structure for JP4 that is similar to that for the CD2022/additive fuels i.e. a steady drop-off is seen following the agent application. Perhaps this can be correlated with the decrease in benzene and toluene emissions although given the small amount of data available, this must remain speculative.

5. Polycyclic Aromatic Hydrocarbons (PAH's)

Figures 54, 55 and 56 show the yields of the volatile polycyclic aromatic hydrocarbons, naphthalene, acenaphthylene, 1,1-biphenyl with and without the application of the agent. As in the emissions of benzene and toluene, considerable decreases of naphthalene and acenaphthylene (76% and 26%) are seen for the JP4 fire although there is an increase (27%) in 1,1-biphenyl. The amount of 1,1-biphenyl found is small however, and given experimental uncertainty, this observed increase must be considered ambiguous.

Figure 57 shows the yields of PAH's recovered from soxhlet extraction of the soot collected on the filters during fires of JP4 and CD2022 plus additive in varying concentrations with the application of AFFF. It is found that total PAH's are reduced compared with JP4 without the application of AFFF. The amount of the reductions are listed in Table 18.

Figures 58-60 show the concentrations of selected PAH's, phenanthrene, fluoranthene and pyrene with and without the use of AFFF. It is seen that generally the use of AFFF produces a small decrease in the amount of compound emitted compared with the case where no agent is applied.

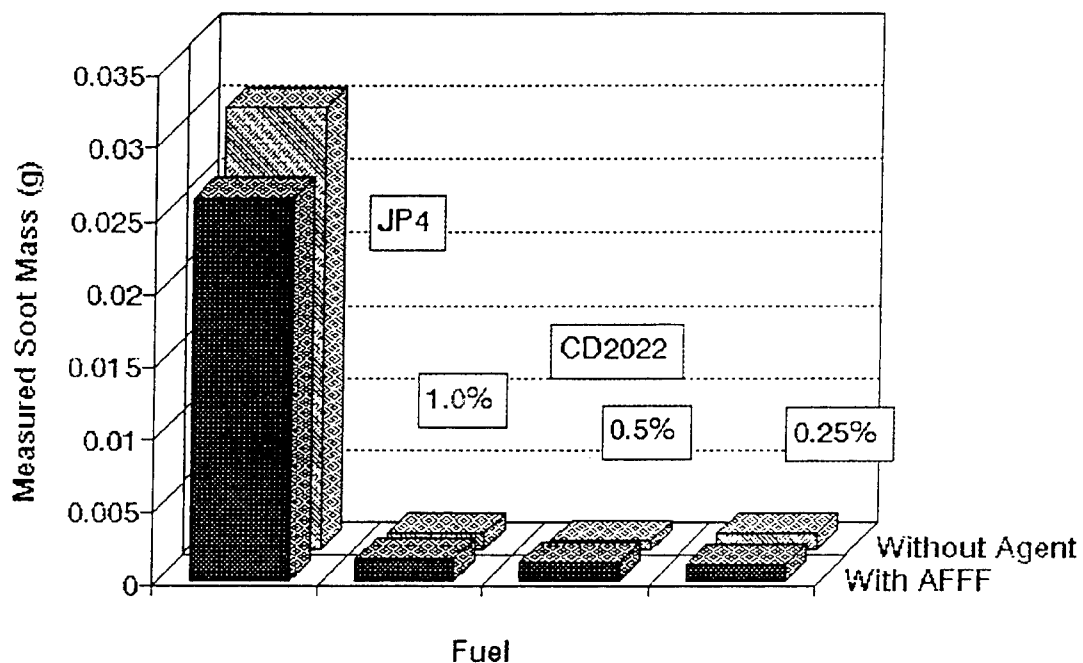


Figure 46. Relative soot masses collected with and without AFFF.

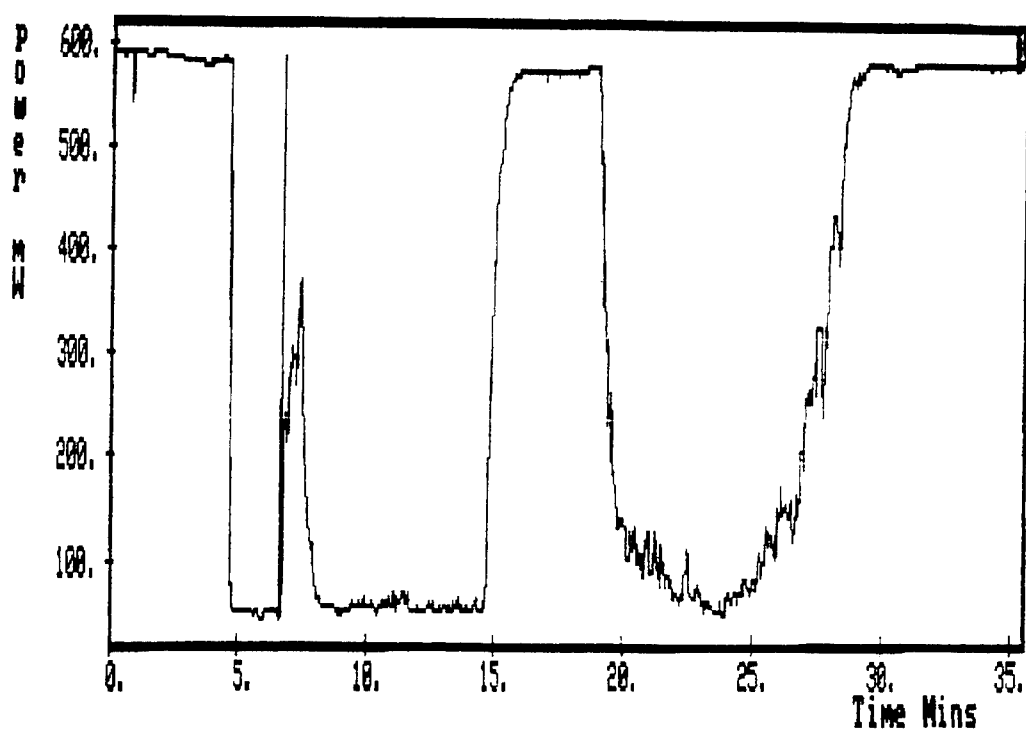


Figure 47. Transmitted light measured during a JP4 fire (AFFF added 2 minutes after ignition).

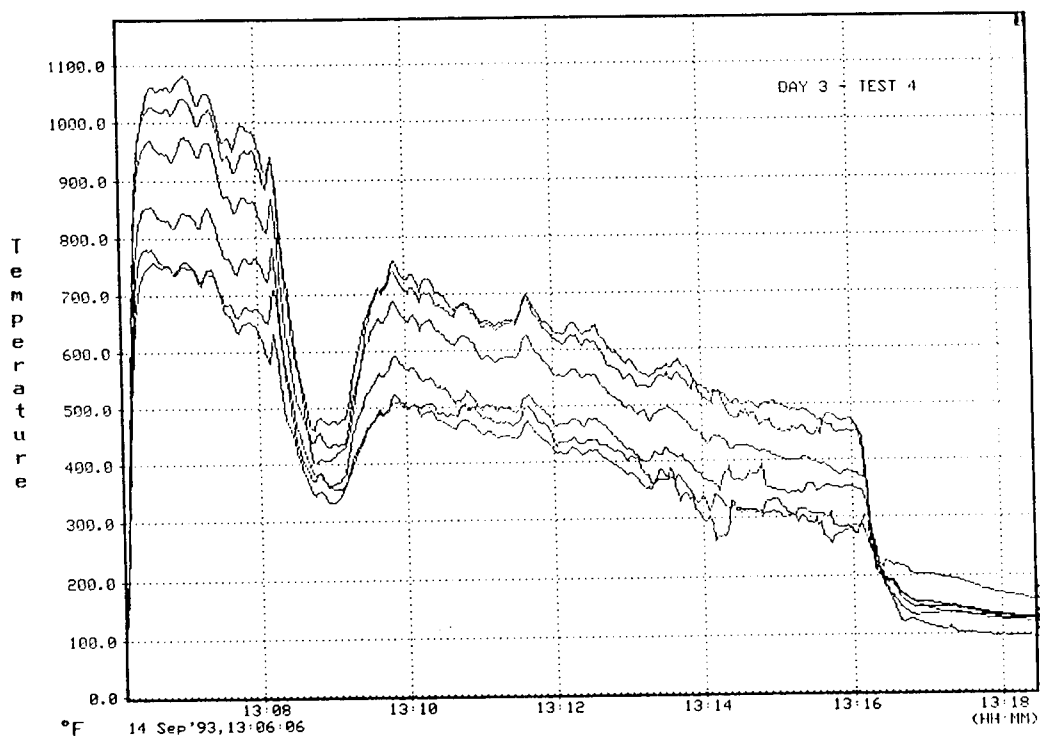


Figure 48. Flame temperature profile for JP4 fire with AFFF added.

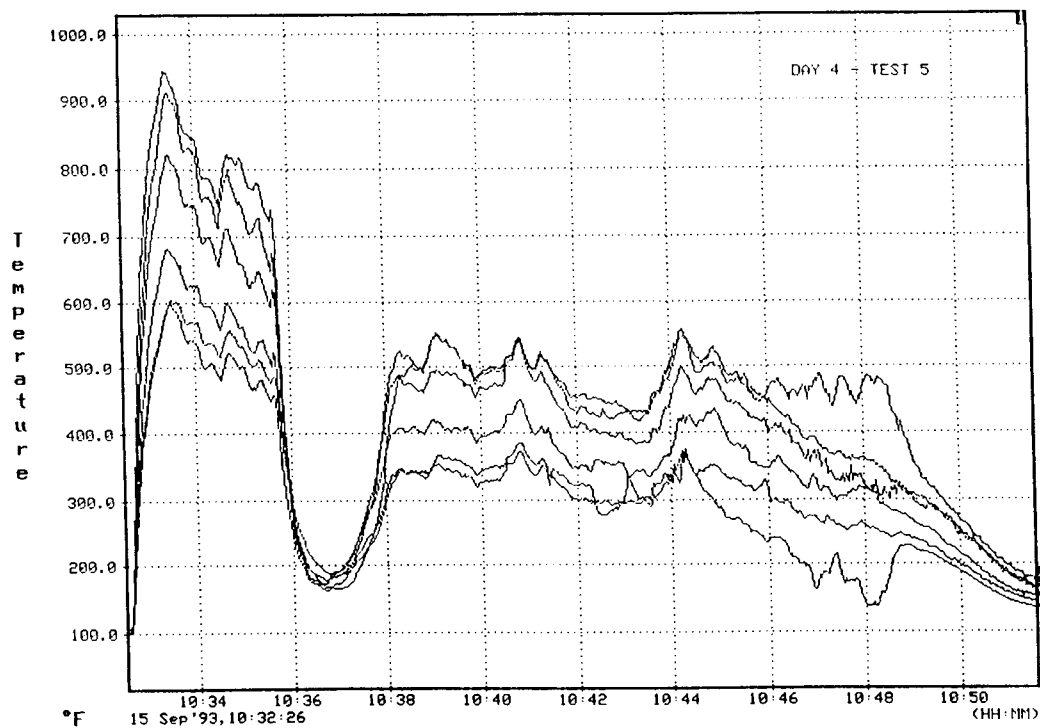


Figure 49. Flame temperature profile for CD2022 + 0.25% fire with AFFF added.

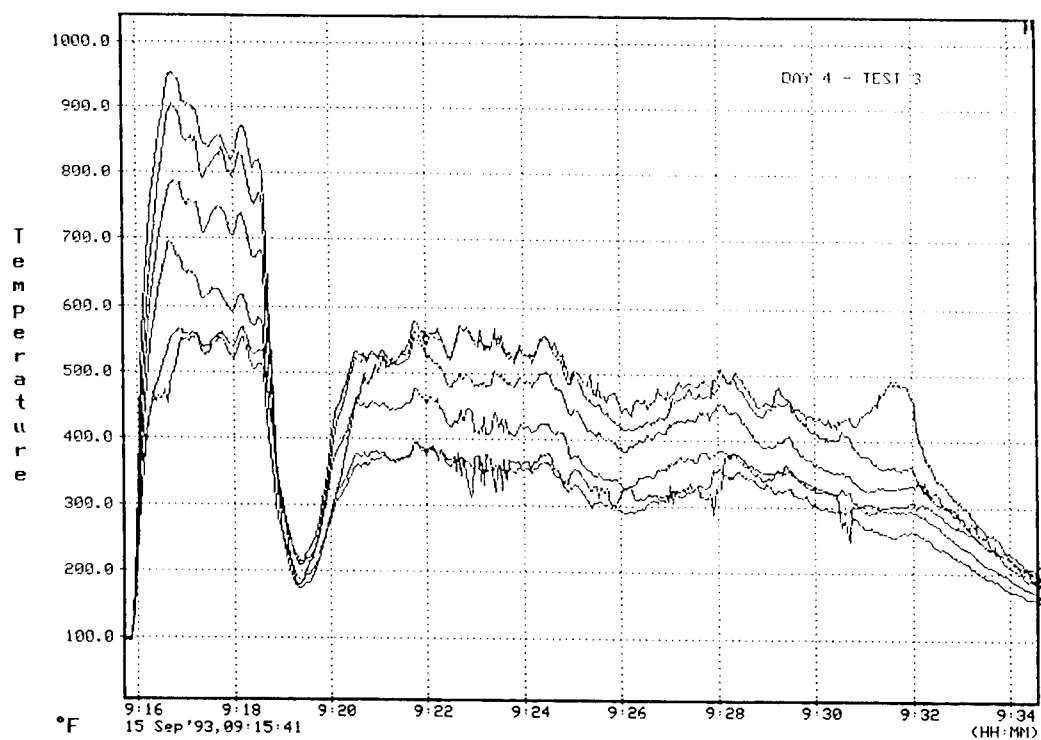


Figure 50. Flame temperature profile for CD2022 + 0.5% fire with AFFF added.

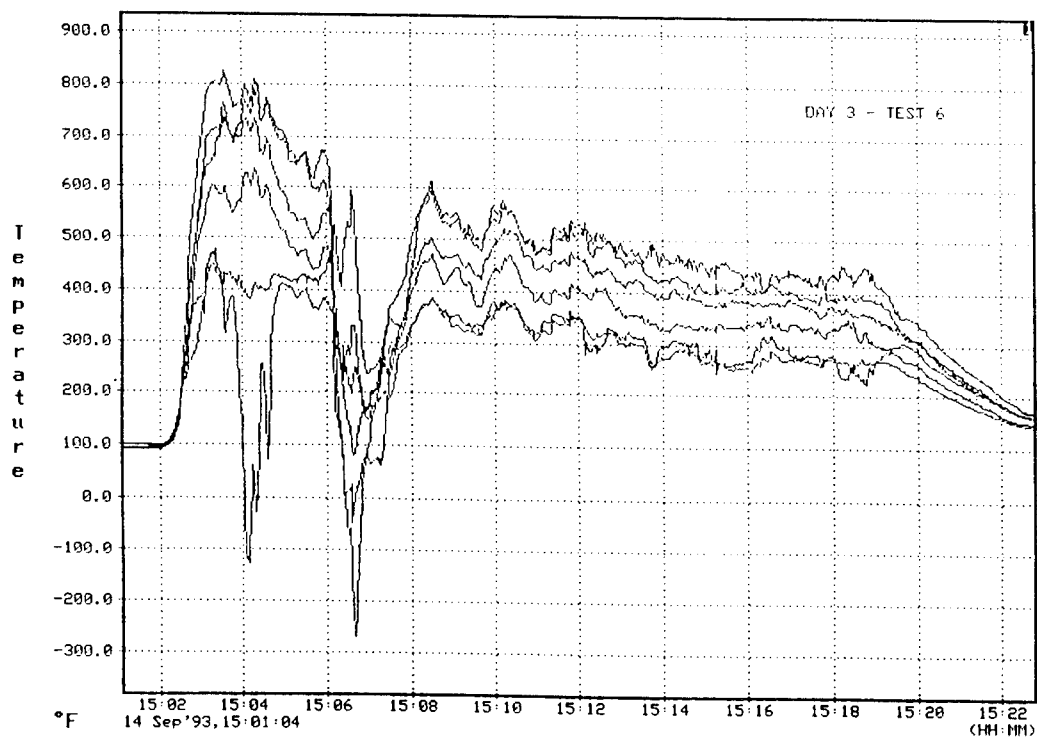


Figure 51. Flame temperature profile for CD2022 + 1.0% fire with AFFF added.

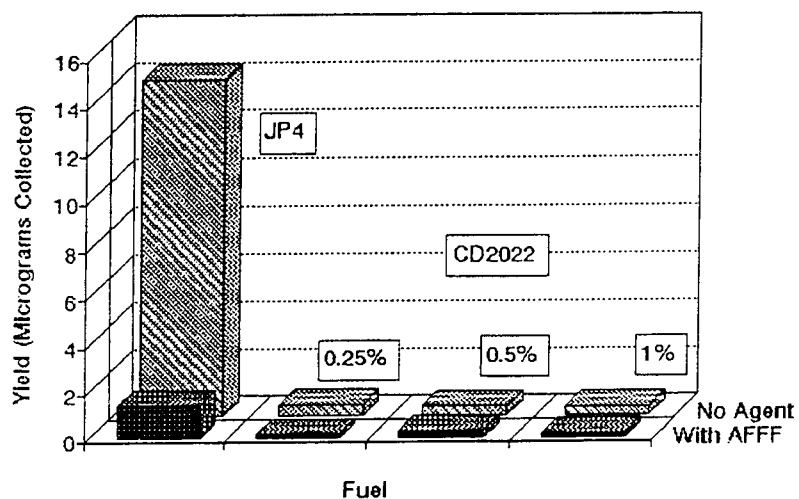


Figure 52. Relative collected masses of benzene from fires of JP4 and CD2022 + additive with and without AFFF.

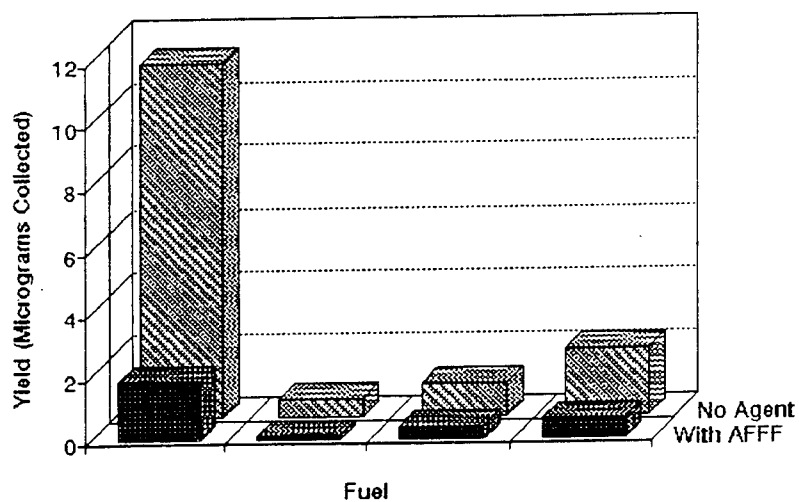


Figure 53. Relative collected masses of toluene from fires of JP4 and CD2022 + additive with and without AFFF.

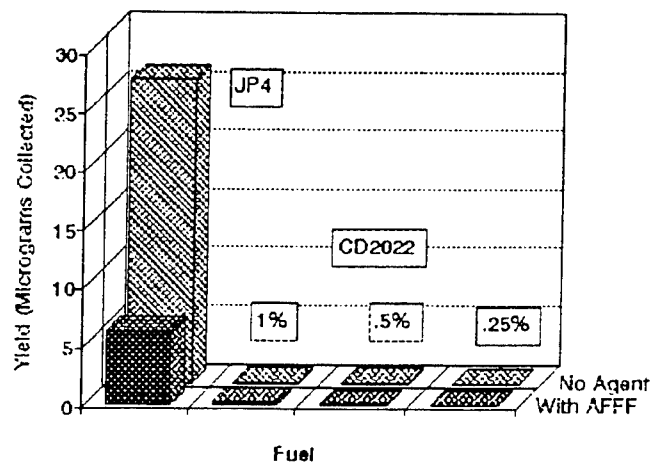


Figure 54. Measured naphthalene concentrations.

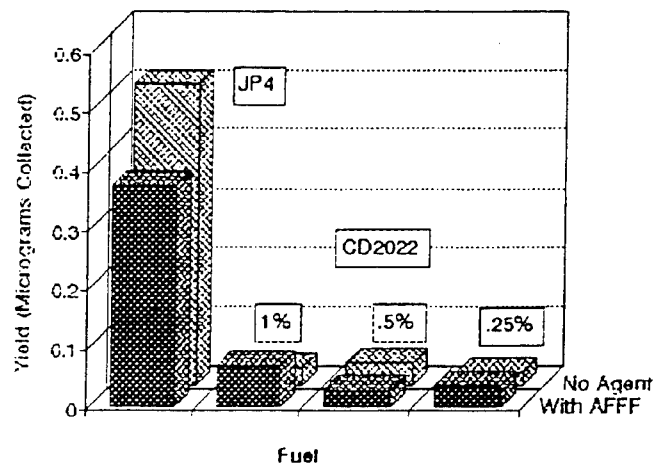


Figure 55. Measured acenaphthylene concentrations.

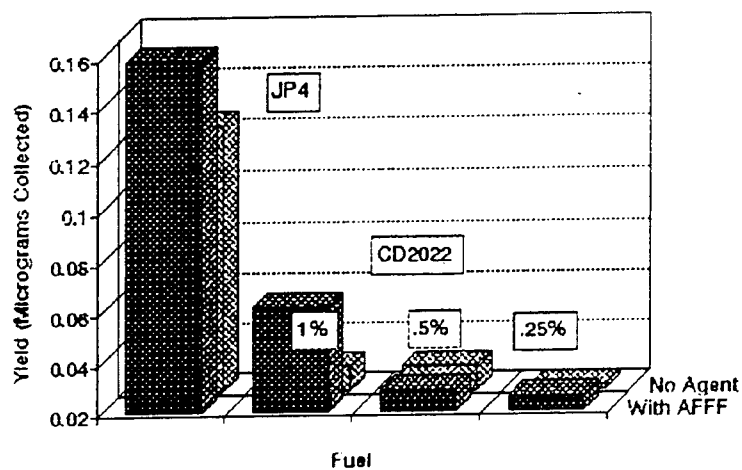


Figure 56. Measured 1,1-biphenyl concentrations.

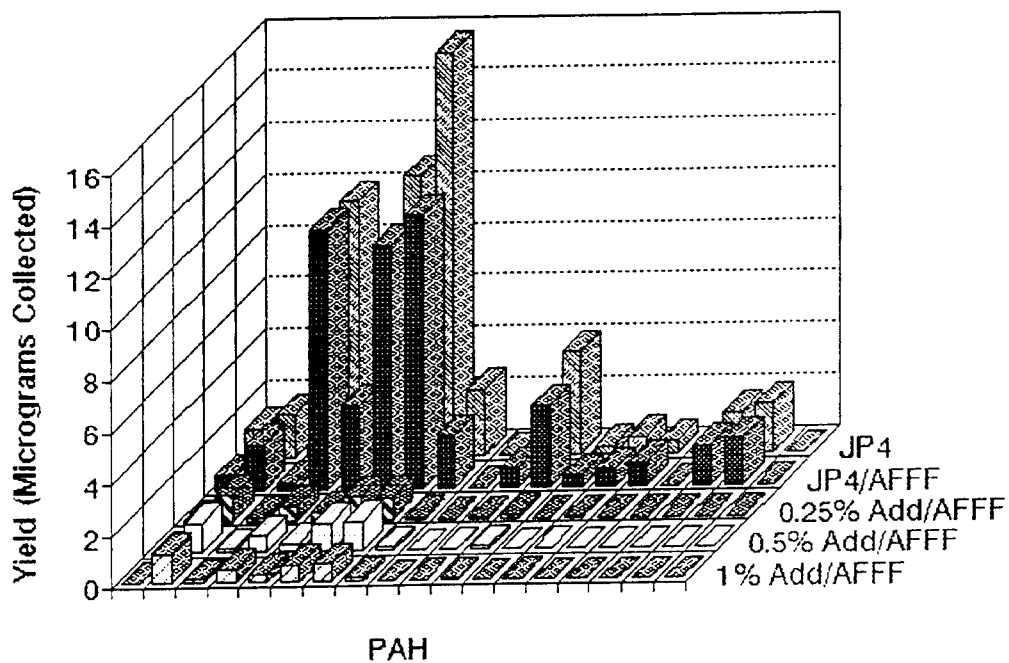


Figure 57. Relative collected masses of non-volatile PAH's with and without AFFF.

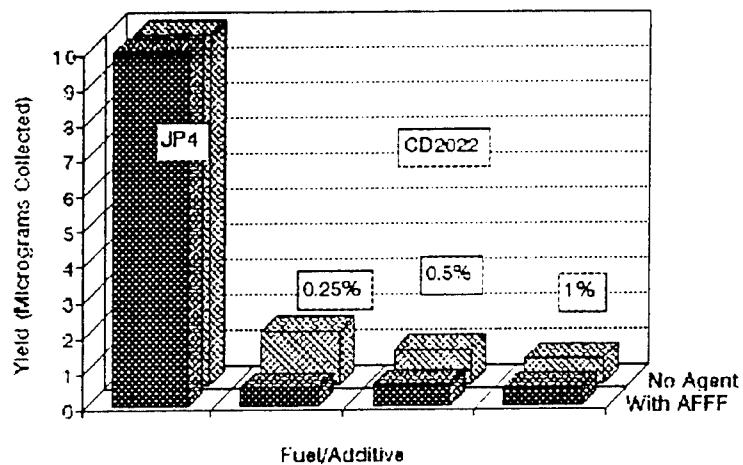


Figure 58. Measured phenanthrene concentrations.

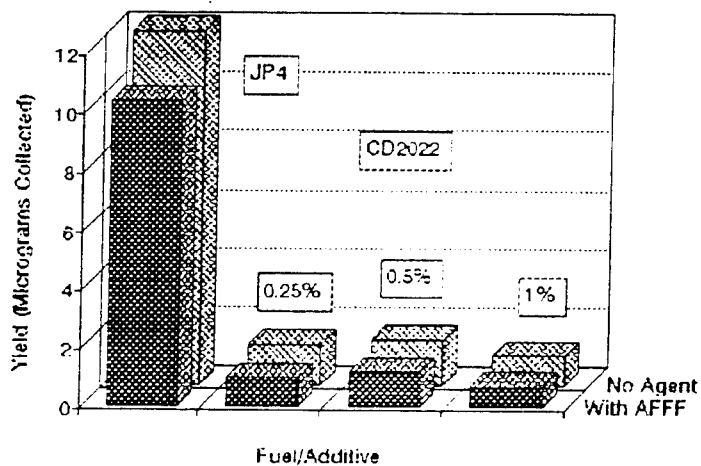


Figure 59. Measured fluoranthene concentrations.

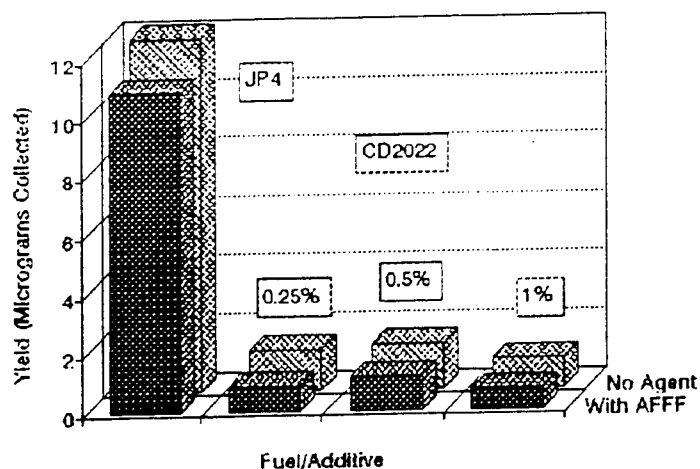


Figure 60. Measured pyrene concentrations.

TABLE 18. REDUCTION IN PAH EMISSIONS FROM FIRES WITH AND WITHOUT AFFF COMPARED TO JP4

FUEL	REDUCTION
JP4	0%
JP4 with AFFF Applied	17%
CD2022 + 0.25% Additive + AFFF	93%
CD2022 + 0.5% Additive + AFFF	89%
CD2022 + 1 % Additive + AFFF	90%

6. Aldehydes

Figures 61 and 62 show the effect of AFFF use on formaldehyde and propionaldehyde emissions. In both cases there is a considerable increase in these emissions. This is observed for the JP4 fire where the increase is a factor of two and for the CD2022 + Additive cases where increases of up to 10 times are seen.

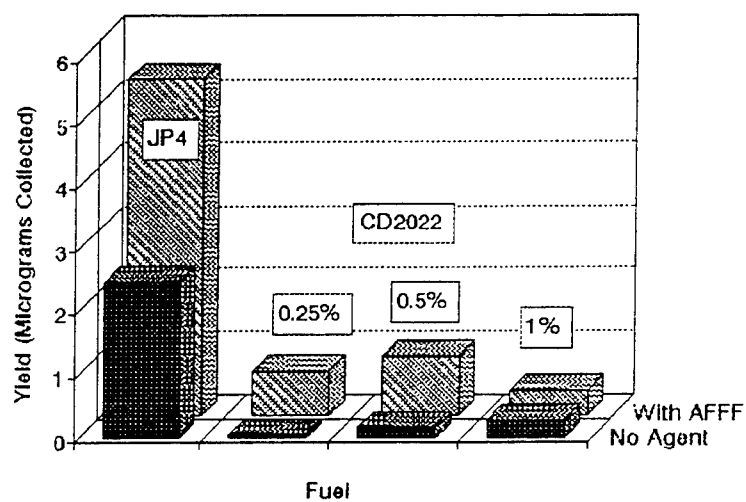


Figure 61. Relative collected masses of formaldehyde with and without AFFF.

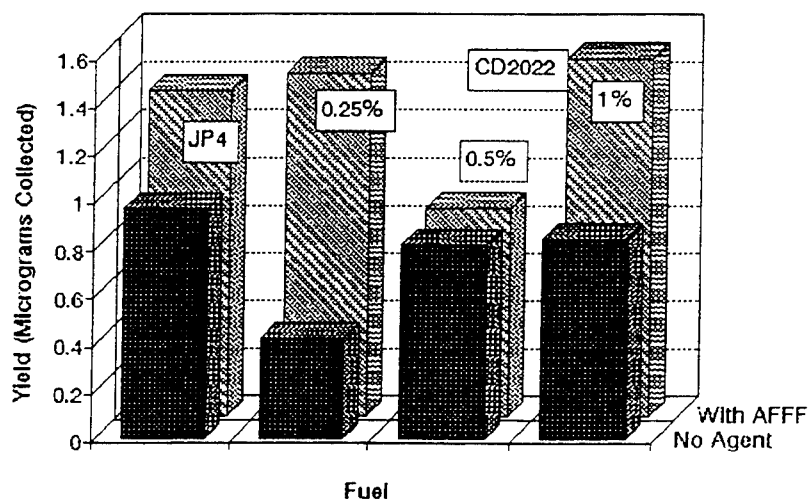


Figure 62. Relative collected masses of propionaldehyde with and without AFFF.

C. DRY CHEMICAL

This agent is used as a fine powder that is sprayed onto a fire from an extinguisher. Delivery is often from hand-held units although larger, truck mounted dispensers are also employed. Potassium bicarbonate KHCO_3 is the principal active ingredient and when it enters the flame zone, a characteristic purple light emission is seen that arises due to excitation of the potassium atoms. The product also contains some silicone compound that enhances deliverability and handling.

In these tests, 20 pounds of dry chemical were injected into fires of JP4 and CD2022 plus 0.25%, 0.5% and 1%, additive.

1. Soot Masses

Figure 63 shows the soot masses collected during the fires of JP4 and CD2022 plus 0.25%, 0.5% and 1% additive, with and without the injection of Dry Chemical. Visual observation suggested that the introduction of the agent produces very little effect on the total soot production but when the filters were weighed, large increases in collected particulate masses were observed. This is due simply to the collection of unconsumed agent.

2. Opacity

Figure 64 shows the effect on the measured opacity of Dry Chemical being introduced into the JP4 fire. A small blip is seen about 2 minutes after the beginning of the fire, this representing a small decrease in opacity. Visual observation of the smoke emitted during this test showed that the smoke went from being very black to a thick grey (figure 66) during the application of the dry chemical. This may account for the slight decrease. Figures 65 and 66 on the other hand shows the effect of dry chemical application on the CD2022/0.5% additive fire and here it is seen that there is a momentary large increase in opacity during the application. This is one of the practical difficulties with the use of dry chemical in that it does lead to an obscuration problem, making it difficult to assess the state of the fire until the powder cloud has dispersed.

3. Flame Temperatures

The effect of the agent on fire temperatures can be seen in figures 68-71. It is seen that in each case the agent produced a decrease of about 300C-400C in the measured temperatures and that this decrease lasted for a period of about 1 minute, roughly the time for the application. In the case of the JP4 fire, the measured temperatures returned to a level similar to that measured at the beginning of the application. For the CD2022/additive fires, the temperature returned to levels similar to those seen in fires where the agent was not used.

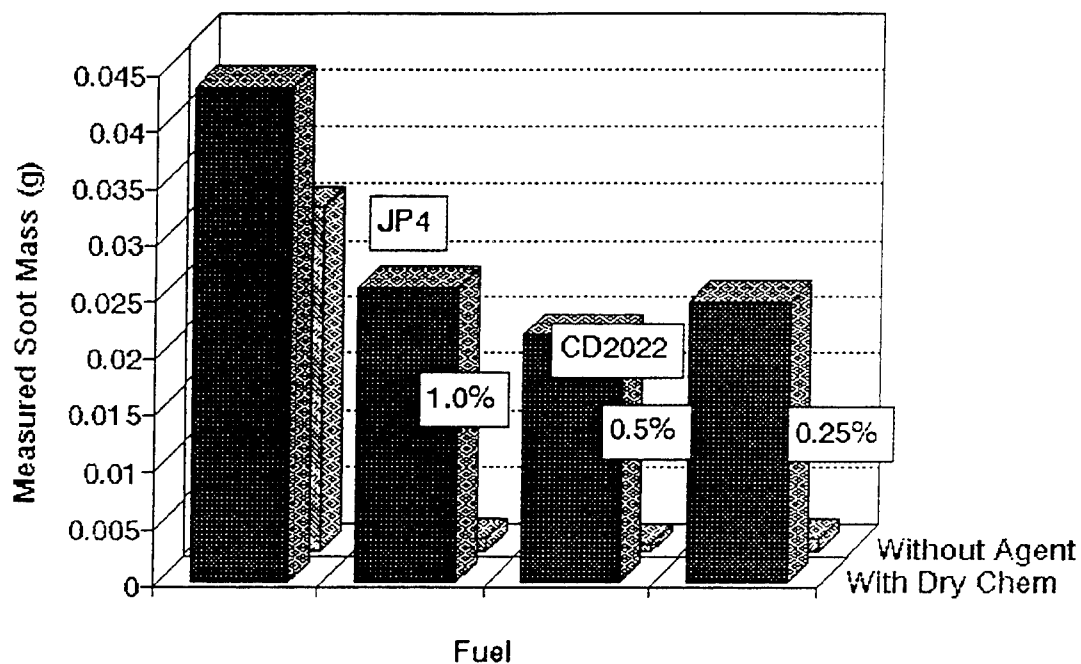


Figure 63. Relative particulate masses collected with and without dry chemical.

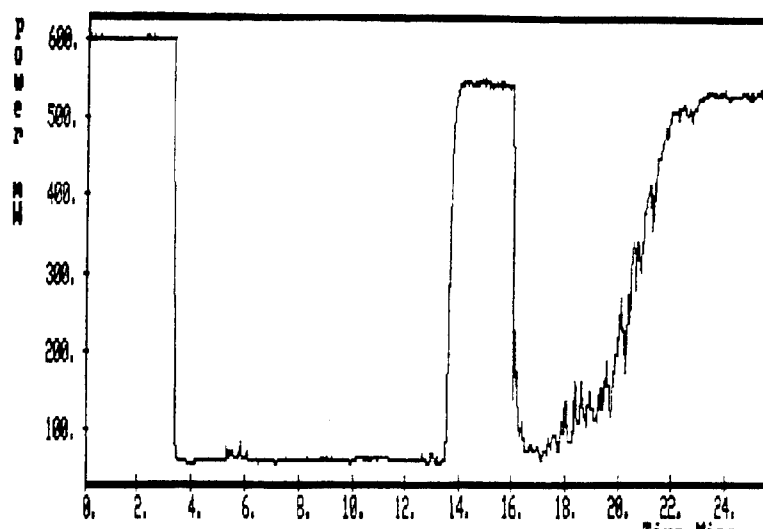


Figure 64. Transmitted light measured during a JP4 fire (dry chemical added 2 minutes after ignition).

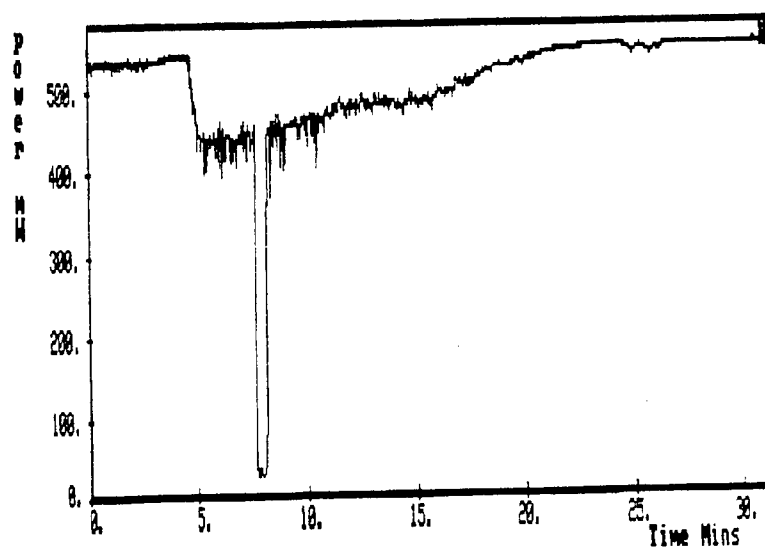


Figure 65. Transmitted light measured during a fire of CD2022 + 0.5% additive (dry chemical added 2 minutes after ignition).

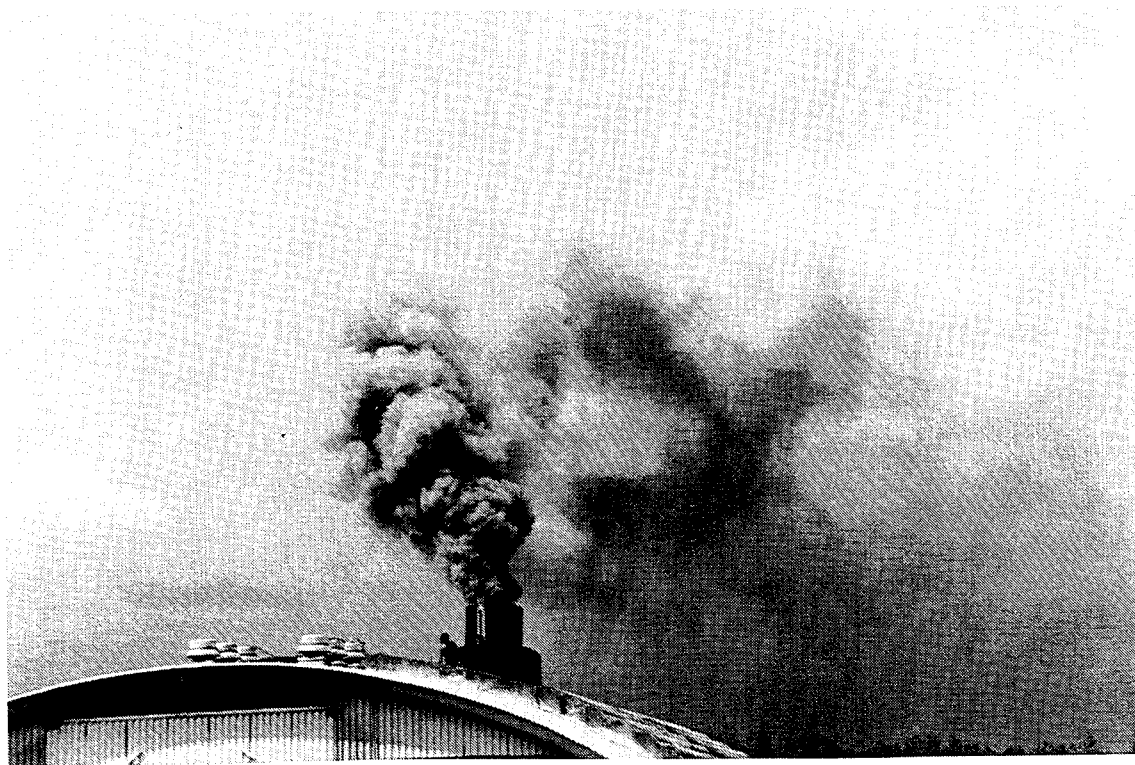


Figure 66. View of smoke emitted during dry chemical application to a JP4 fire.

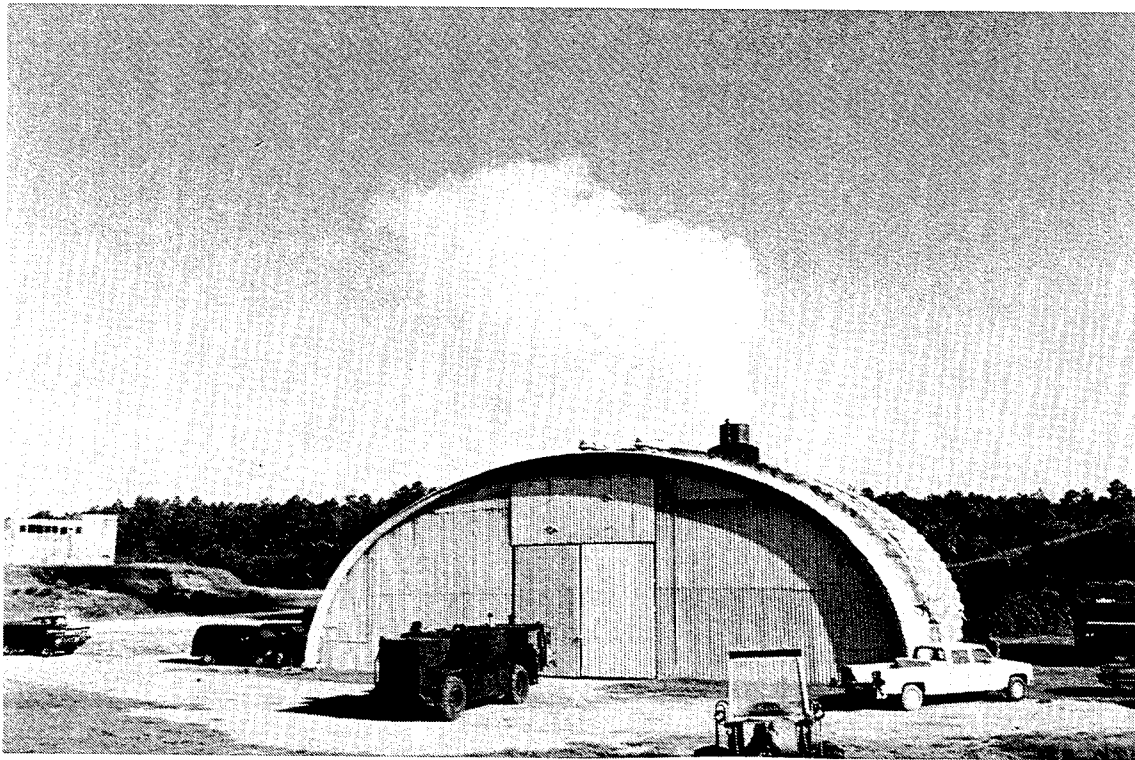


Figure 67. View of smoke emitted during dry chemical application to a fire of CD2022 + 0.5% additive.

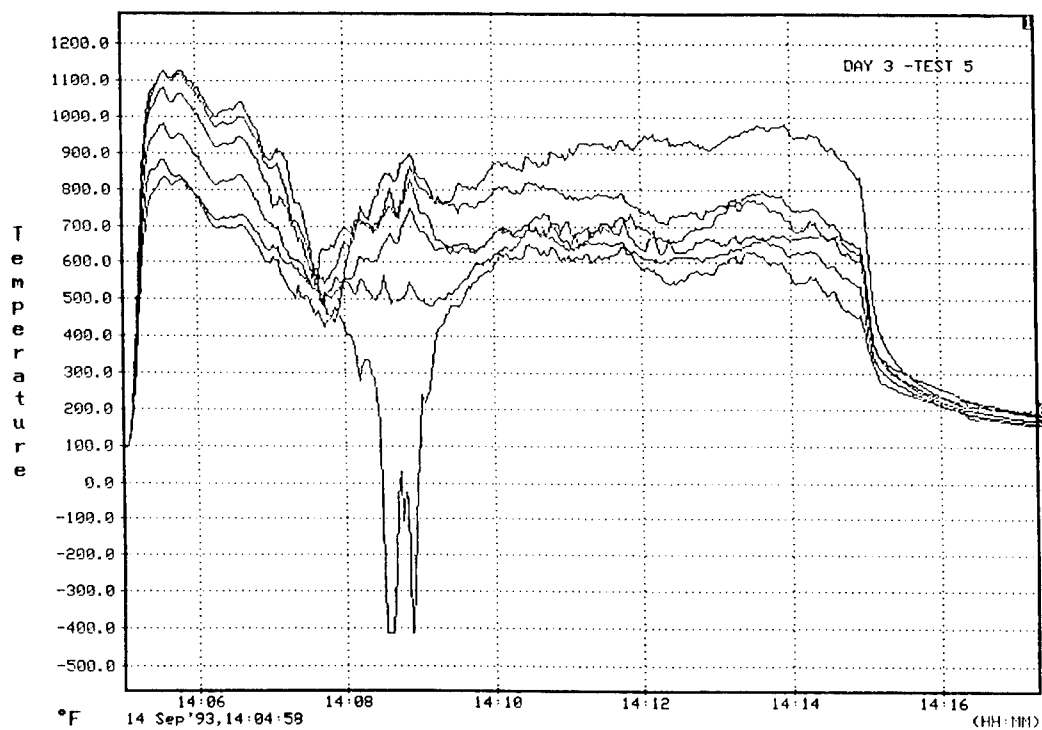


Figure 68. Temperature profile for JP4 with dry chemical.

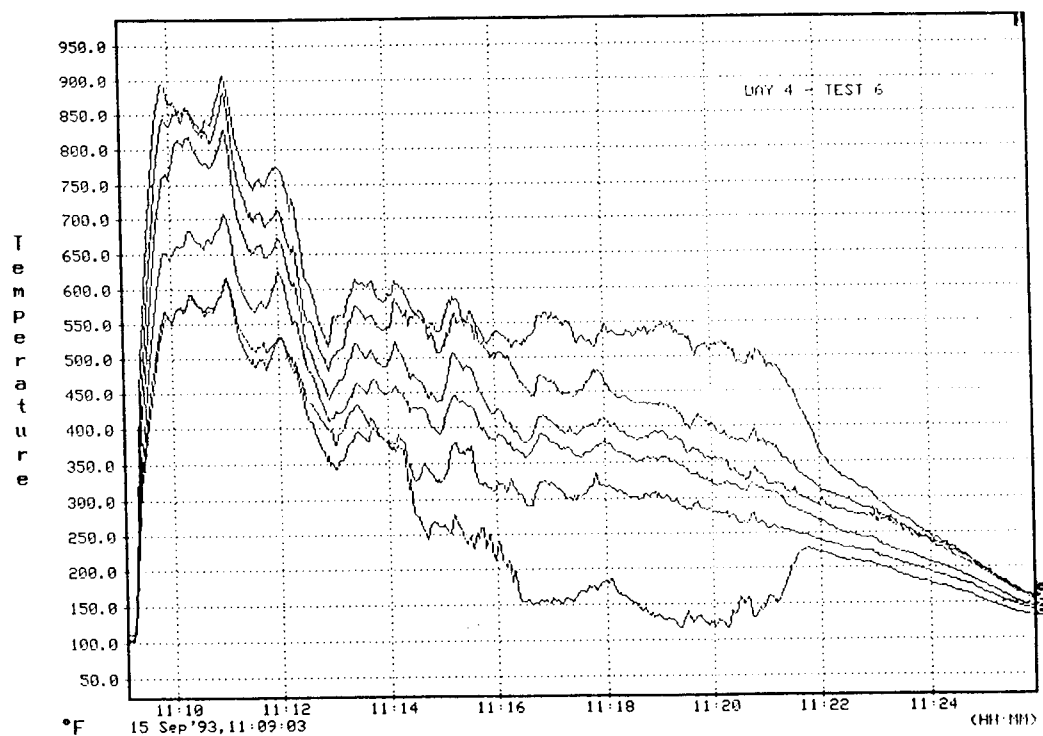


Figure 69. Temperature profile for CD2022 + 0.25% with dry chemical.

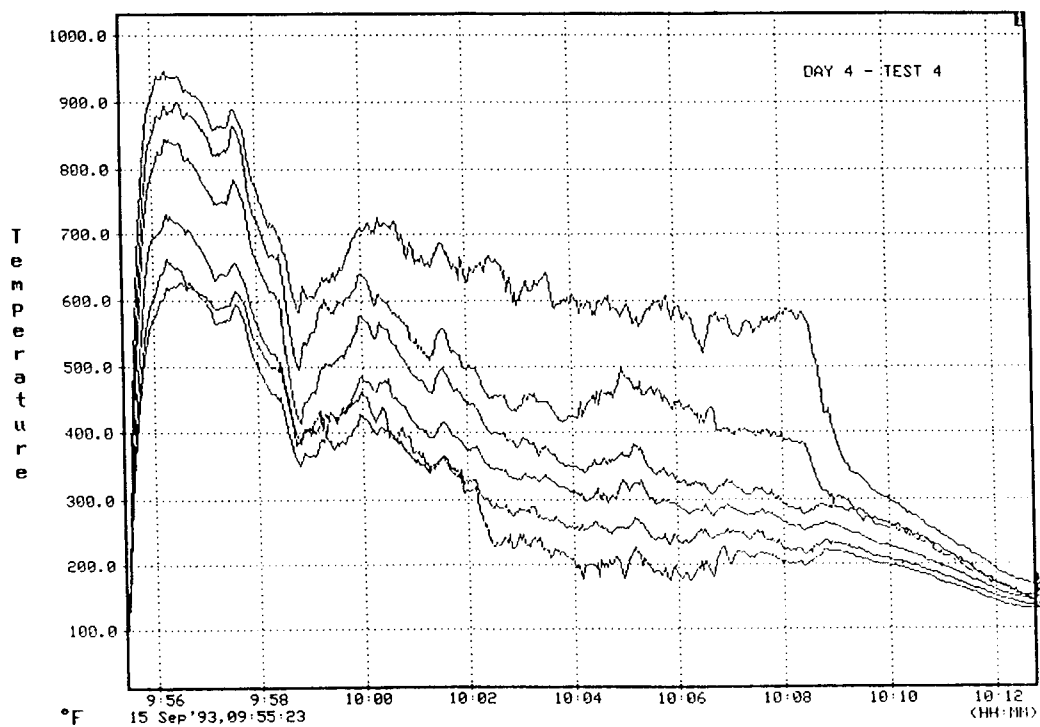


Figure 70. Temperature profile for CD2022 + 0.5% with dry chemical.

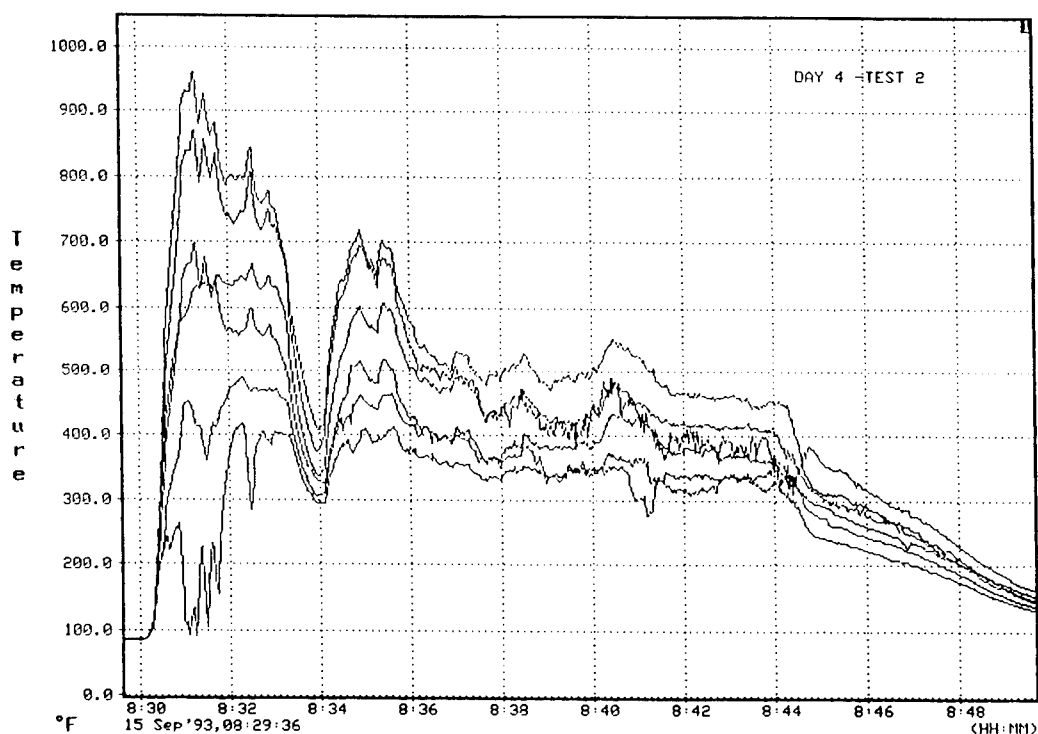


Figure 71. Temperature profile for CD2022 + 1.0% with dry chemical.

4. Volatile Organic Carbon's (VOC's)

Figures 72 and 73 show the relative amounts of benzene and toluene released during the JP4 and CD2022/additive fires with and without Dry Chemical being introduced. As in the case of the AFFF application, a large decrease in benzene and toluene emissions (88% and 54% respectively) are seen for the JP4 fire. Again, as in the case of AFFF, additional peaks appear in the chromatograms that have been identified as being due to unburned fuel. A similar mechanism involving the lowering of fire temperatures can perhaps be invoked to explain these observations.

5. Polycyclic Aromatic Hydrocarbons (PAH's)

Figure 74, 75 and 76 show the concentrations of Naphthalene, acenaphthylene and 1,1-biphenyl measured for fires of JP4 and CD2022 plus additives with and without the application of Dry Chemical. Large increases in the concentration of these species with the use of the agent in the JP4 fire were seen but this was not observed for the CD2022 fires. Figure 77 shows the relative concentrations of PAH's recovered from the filter residues. Figures 78-80 show the concentrations of phenanthrene, fluoranthene and pyrene with and without the application of dry chemical. Generally it is found that the application of dry chemical leads to a reduction in non-volatile PAH yield.

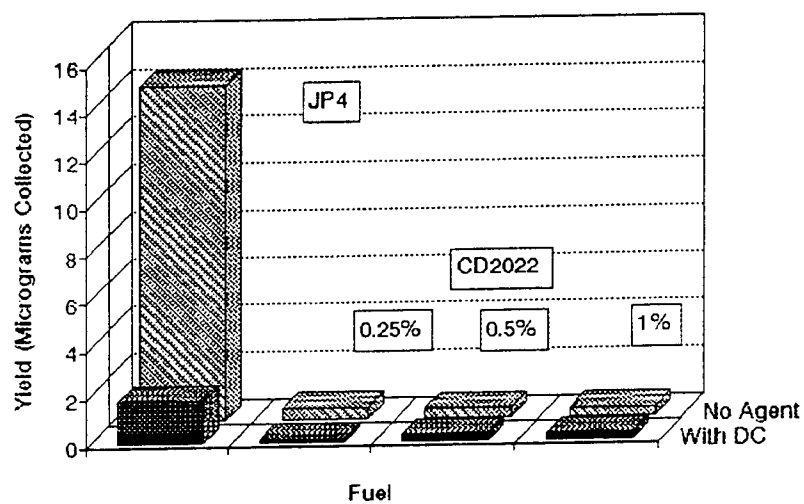


Figure 72. Relative collected masses of benzene with and without dry chemical.

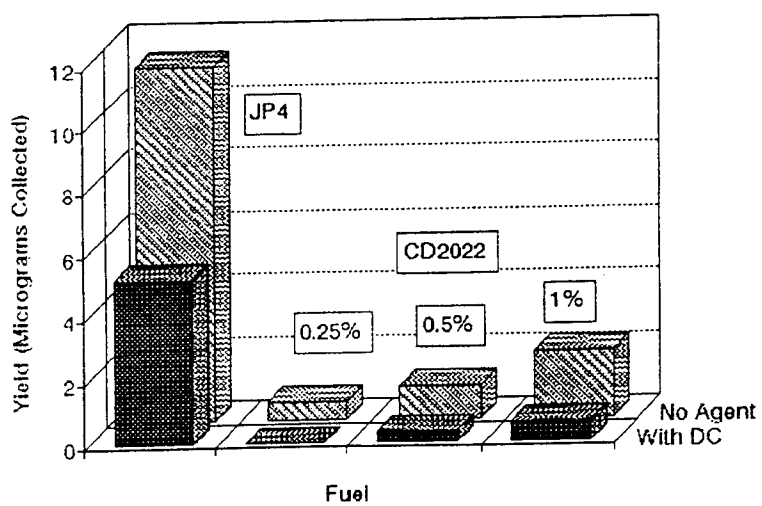


Figure 73. Relative collected masses of toluene with and without dry chemical.

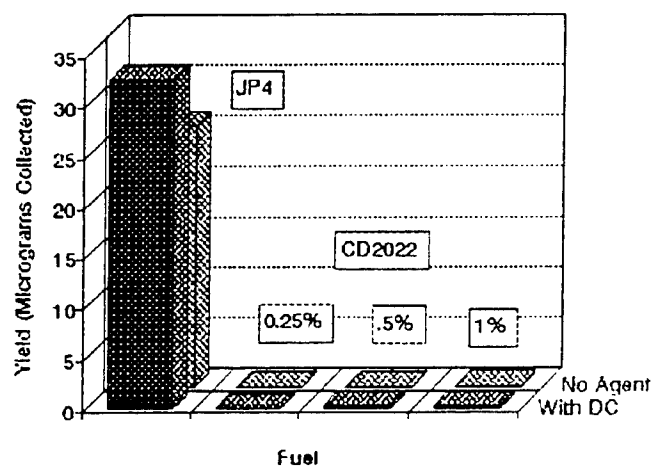


Figure 74. Measured naphthalene concentrations.

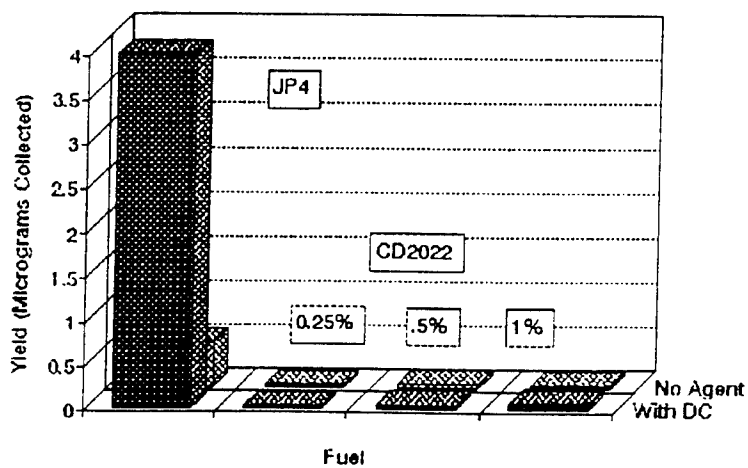


Figure 75. Measured acenaphthylene concentrations.

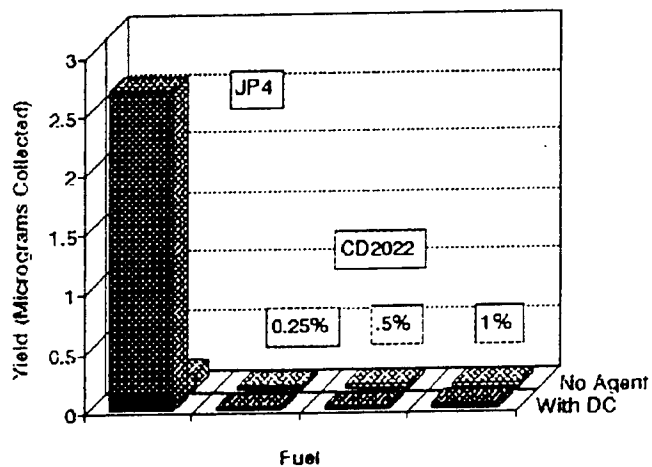


Figure 76. Measured 1,1-biphenyl concentrations.

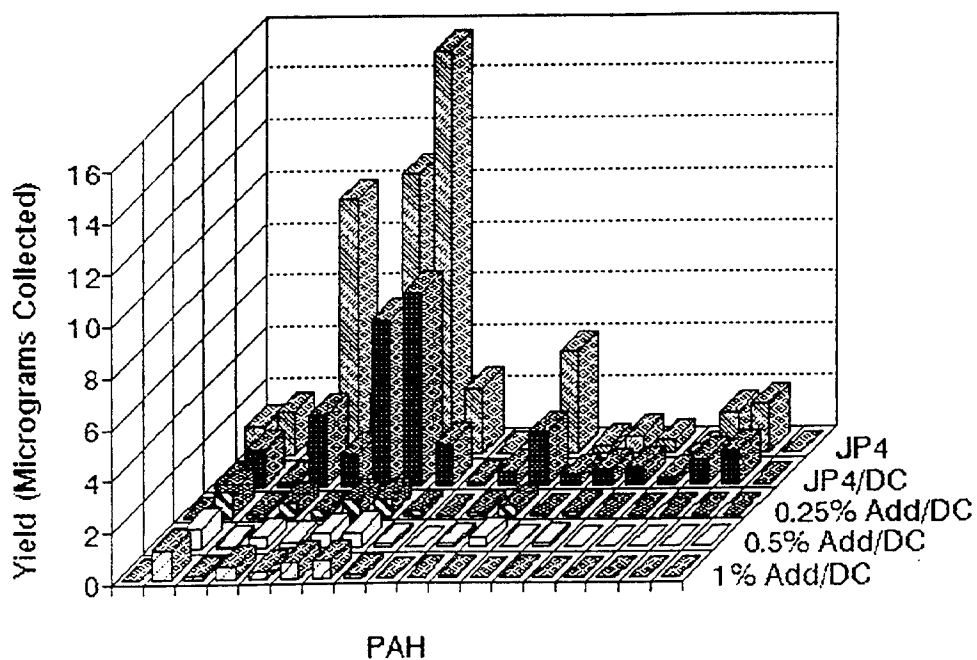


Figure 77. Relative collected masses of non-volatile PAH's with and without dry chemical.

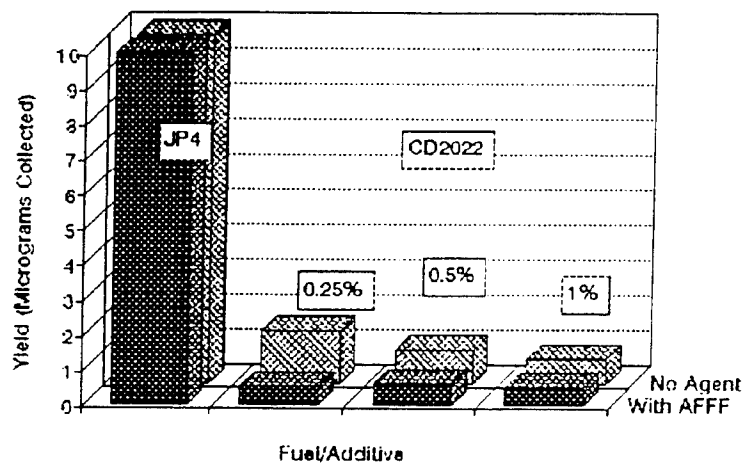


Figure 78. Measured phenanthrene concentrations.

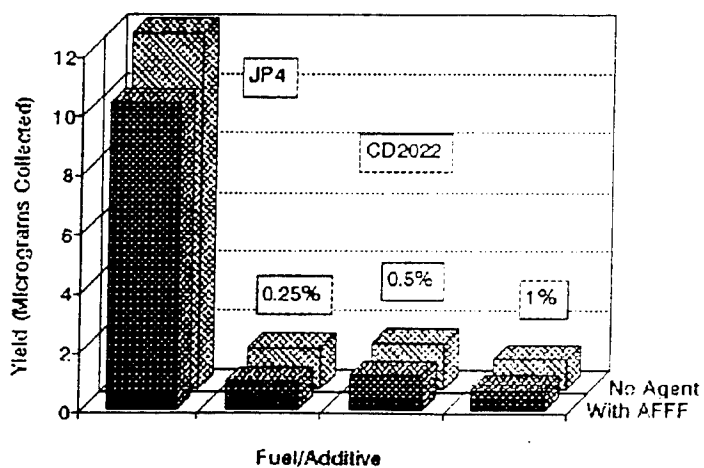


Figure 79. Measured fluoranthene concentrations.

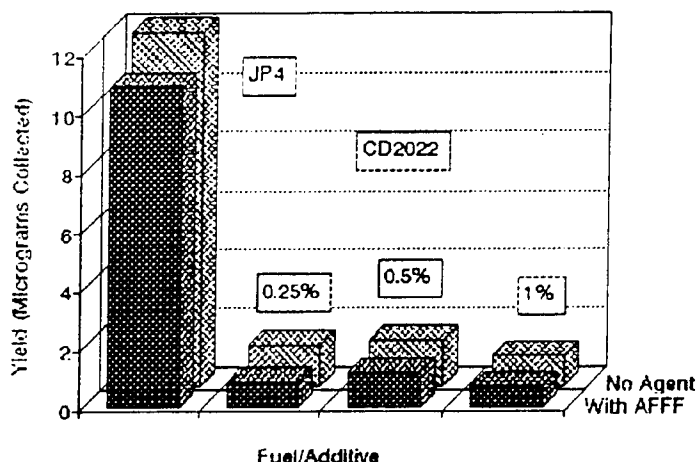


Figure 80. Measured pyrene concentrations.

6. Aldehydes

Figures 81 and 82 show the effect of Dry Chemical usage on aldehyde emissions. There is seen to be an overall increase in the emissions of formaldehyde and propionaldehyde when the agent is used with the CD2022 + Additive fuels. JP4 however displays a dramatic decrease in formaldehyde emission but a large increase in propionaldehyde emission.

D. HALON 1211

Halon 1211 or bromochlorodifluoromethane, CBrClF_2 is a very efficient extinguishing agent. Its mechanism of operation is believed to involve the removal of hydrogen, oxygen and hydroxyl radicals that are responsible for the propagation of the combustion process, via reaction with halogenated radical species released during the decomposition of the halon in the fire. Halons are now considered to be a major ozone depleting chemical and their use is restricted. Halons are not generally used for firefighter training. Although not considered to be particularly toxic at the concentration levels necessary for their effectiveness (5-6%), the combustion products arising from their use may be a greater cause for concern. In this study, fires of JP4 and CD2022 plus additives were subjected to halon 1211 injection and the emission products measured as before. Twenty pounds of halon were used for each test.

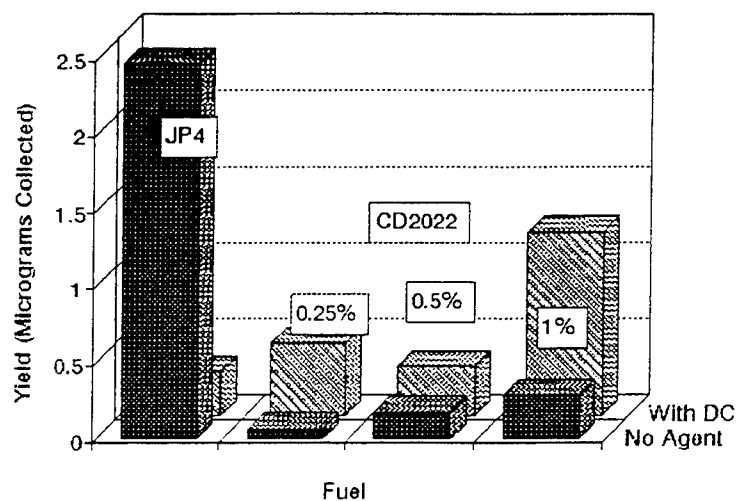


Figure 81. Relative collected masses of formaldehyde with and without dry chemical.

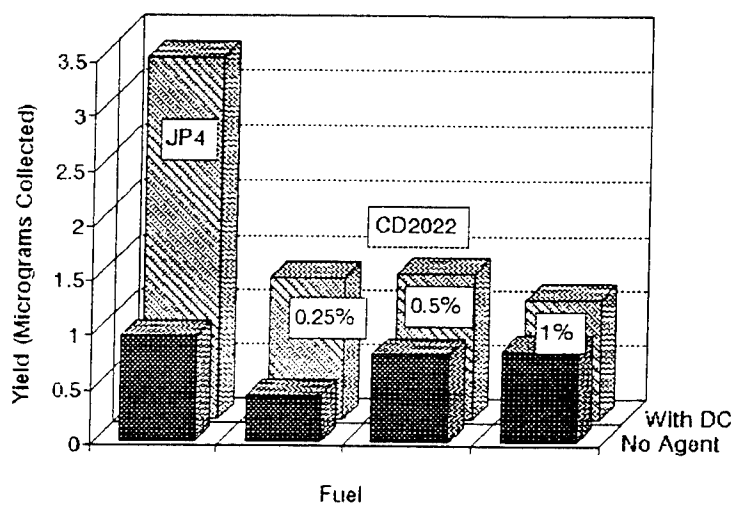


Figure 82. Relative collected masses of propionaldehyde with and without dry chemical.

1. Soot Masses

Organic halogenated compounds not only efficiently extinguish fires, they also greatly enhance soot formation. This was clearly seen during these tests. Figure 83 shows the relative soot masses measured during the fires. It must be remembered that the halon is only present for a short time during the fires (20% of the JP4 burn time, 12% of the CD2022 times) and so its action is much stronger than is immediately apparent from the figure.

2. Opacity

Figure 84 shows the effect on the opacity when halon is introduced into a fire of CD2022 + 1% additive. This effect is also illustrated in figures 85 and 86 which show the stack emission before and during the halon injection.

3. Flame Temperatures

It is seen from figures 87-90 that halon injection produces a decrease in measured flame temperatures of between 200 and 300C.

4. Volatile Organic Carbon's (VOC's)

Figures 91 and 92 show the relative amounts of benzene and toluene emitted with and without the injection of Halon 1211. Again a large decrease (77%) in benzene emission and toluene emission (58%) is observed, in addition to unburned fuel components.

5. Polycyclic Aromatic Hydrocarbons (PAH's)

Figures 93, 94 and 95 show the measured concentrations of naphthalene, acenaphthylene and 1,1-biphenyl emitted with and without the application of halon. Large increases in the latter two compounds are seen. A large increase in soot emission was seen with the injection of halon and this is the reason for the enhancement of these compounds.

Figure 96 shows the yields of PAH's recovered from the filter residues and figures 97-99, the yields of phenanthrene, fluoranthene and pyrene with and without the application of halon. It is seen that there is a significant increase in non-volatile PAH emission when halon is used with JP4 but increases seen with the CD2022 + additive fires are rather small. This may indicate that the additive is able to counteract enhanced PAH production due to the halogens released into the fires from the halon.

6. Aldehydes

Figures 100 and 101 show the effects of halon usage on aldehyde emissions. The formaldehyde results are equivocal for the CD2022 + Additive fuels and overall one can say that there is little change seen. JP4 however displays a dramatic formaldehyde decrease similar to that seen for the Dry Chemical test. Increases in propionaldehyde emission are seen for all cases.

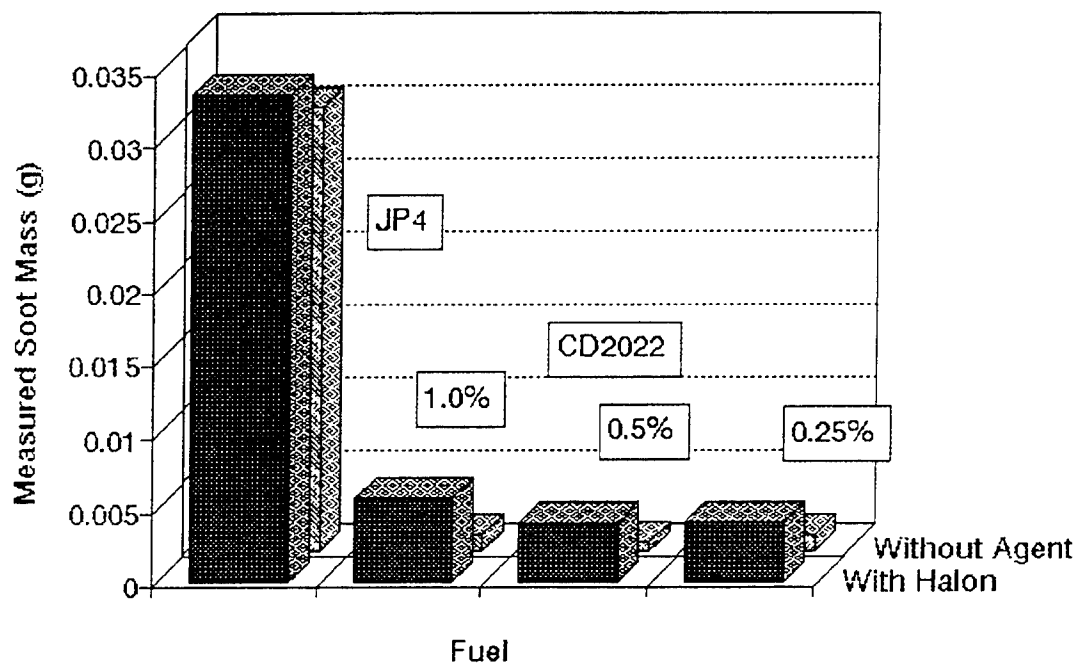


Figure 83. Relative soot masses collected with and without halon.

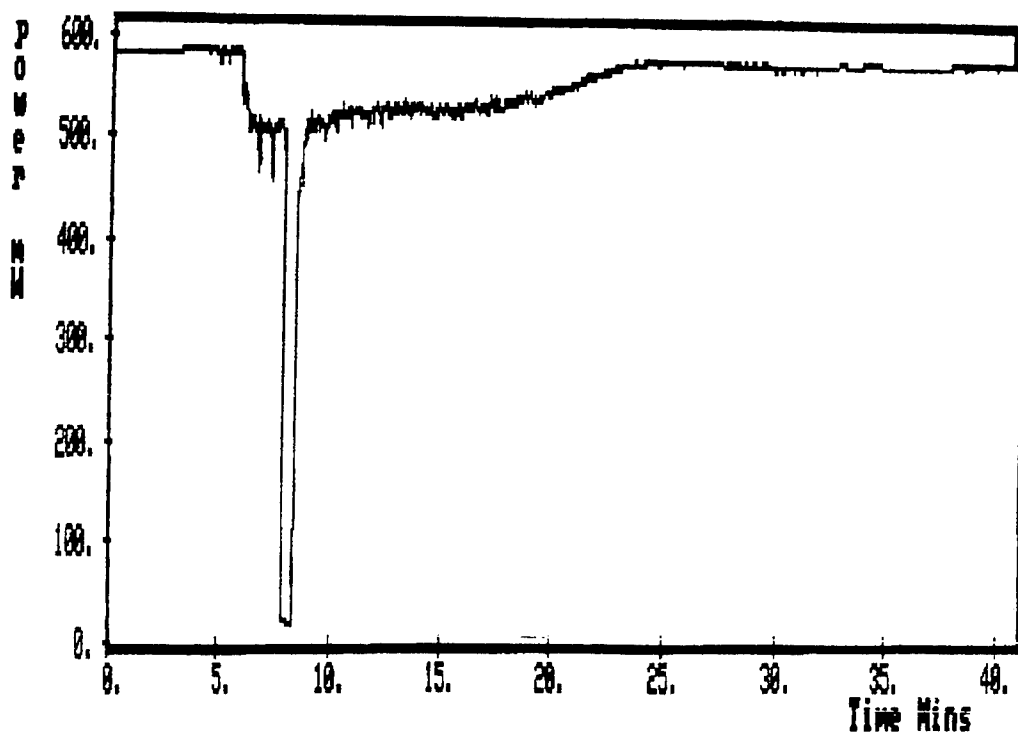


Figure 84. Transmitted light measured during a fire of CD2022 + 1% additive (halon added 2 minutes after ignition).

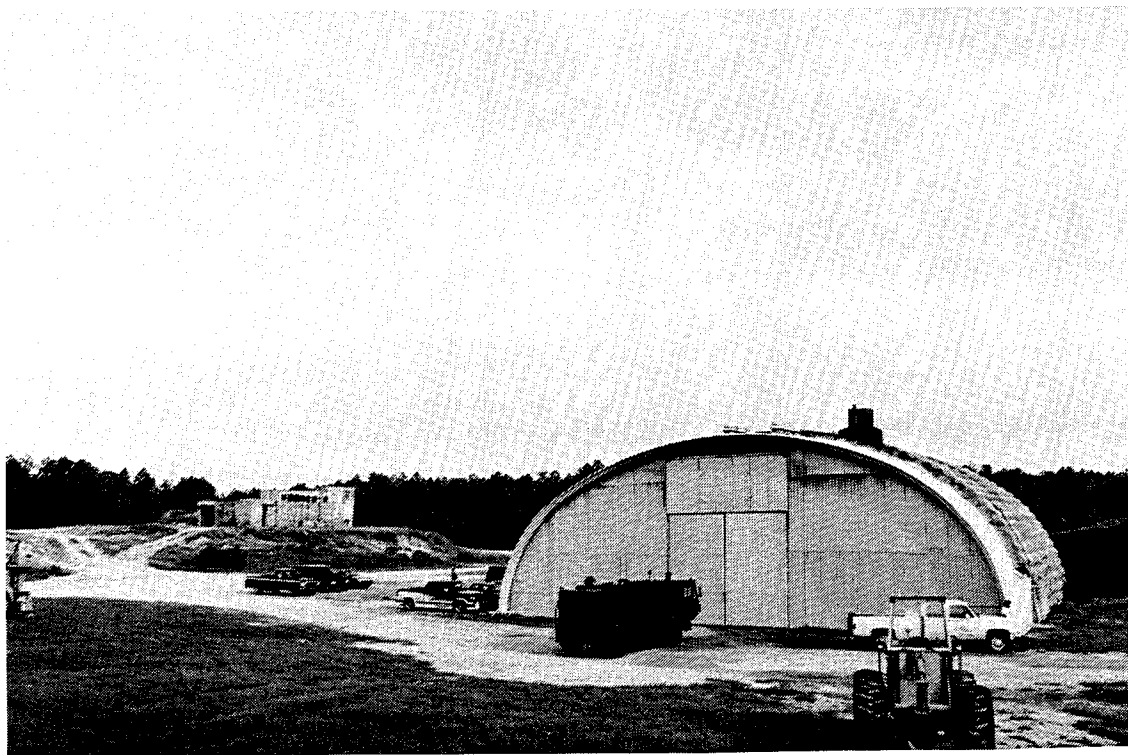


Figure 85. View of smoke stack during a fire of CD2022 + 0.5% additive prior to injection of halon.

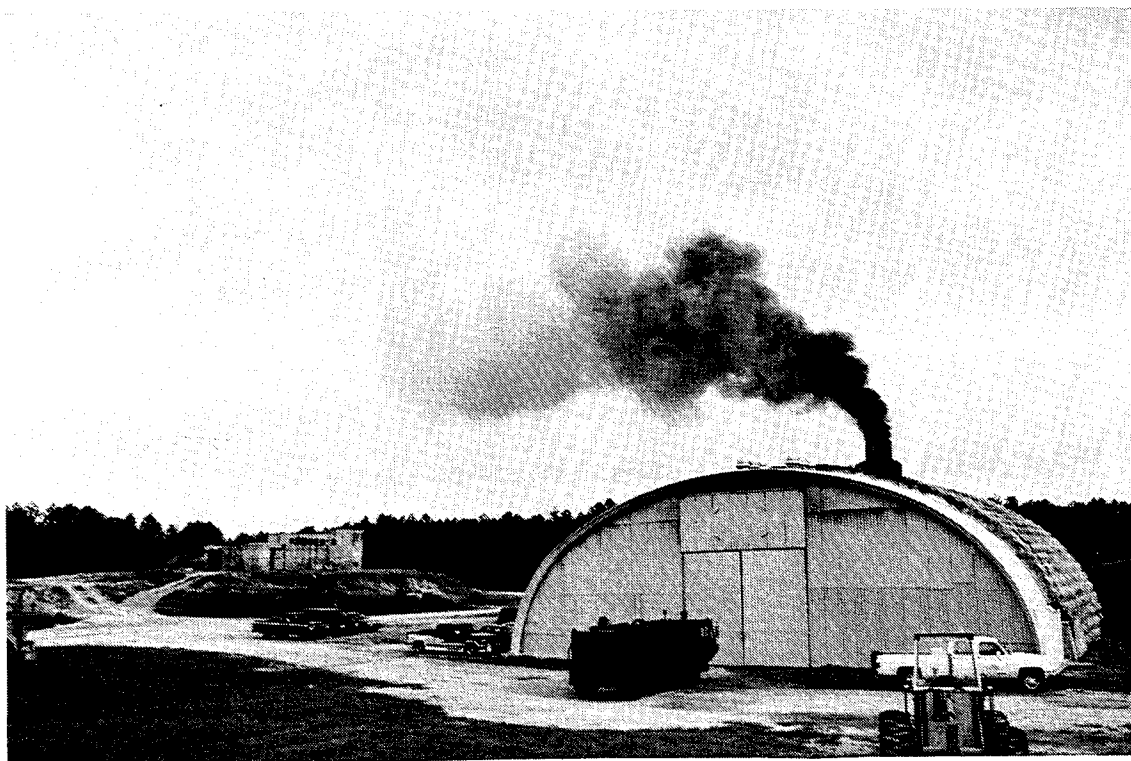


Figure 86. View of smoke emitted during application of halon to a fire of CD2022 + 0.5% additive.

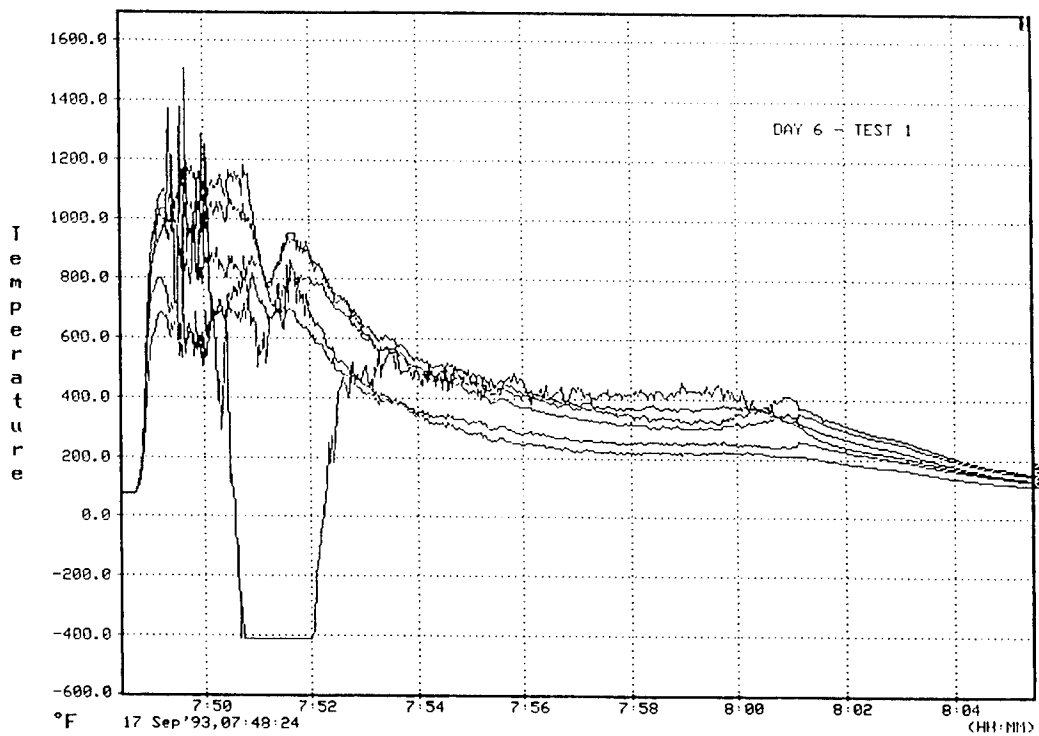


Figure 87. Temperature profile for JP4 with halon.

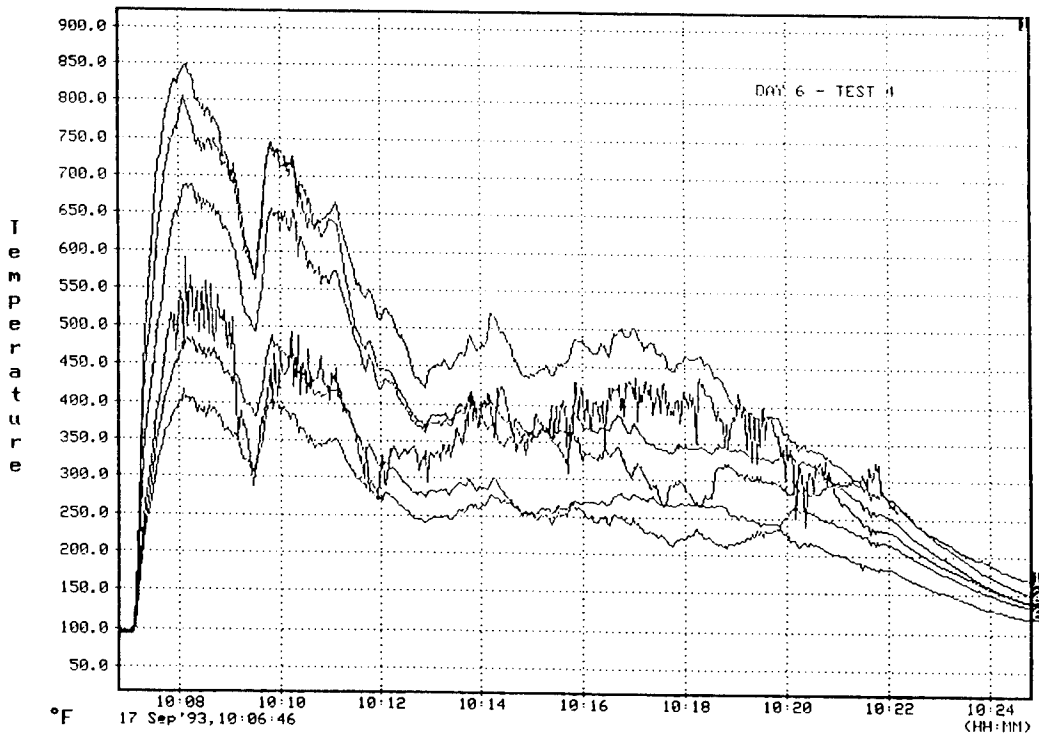


Figure 88. Temperature profile for CD2022 + 0.25% with halon.

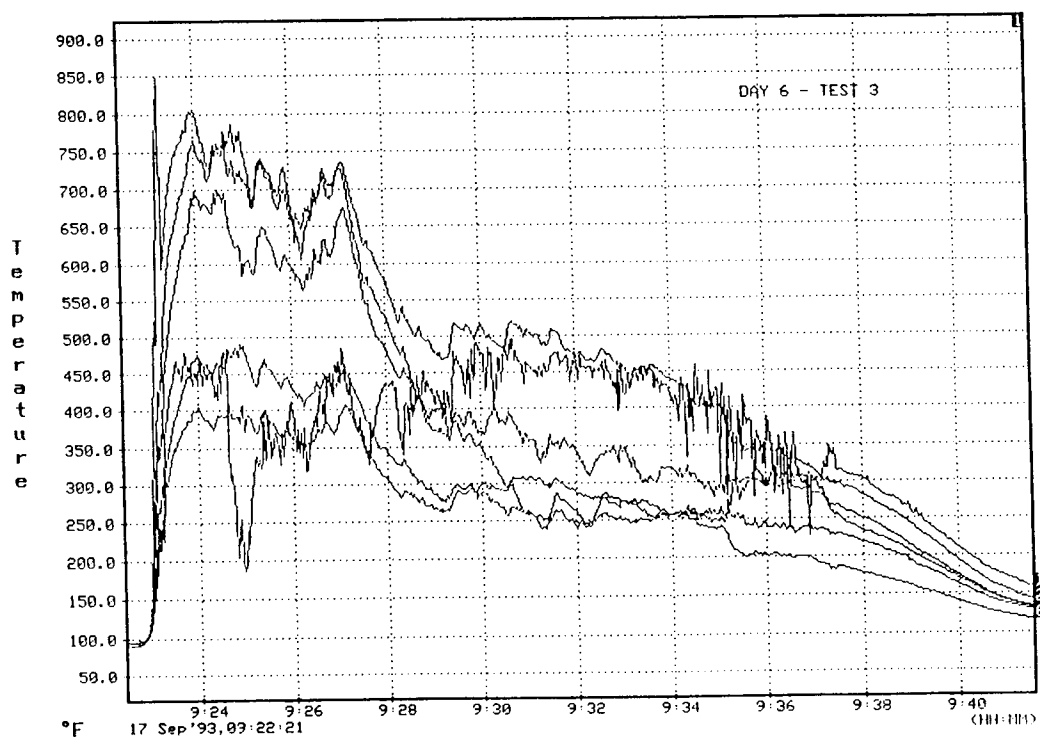


Figure 89. Temperature profile for CD2022 + 0.5% with halon.

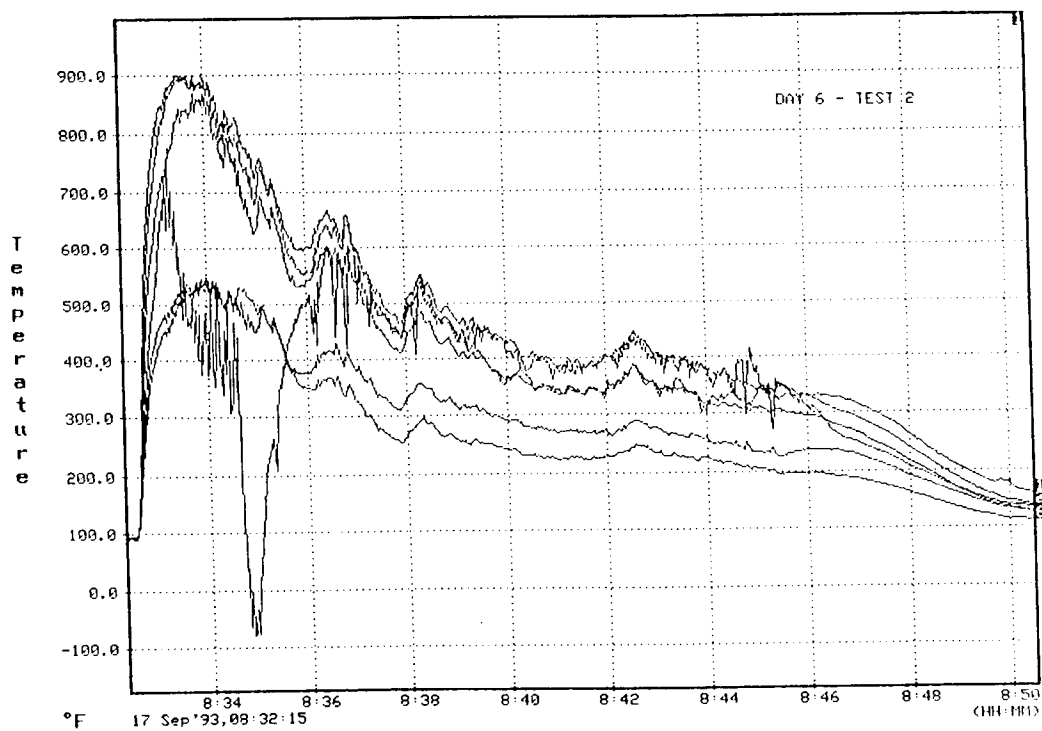


Figure 90. Temperature profile for CD2022 + 1.0% with halon.

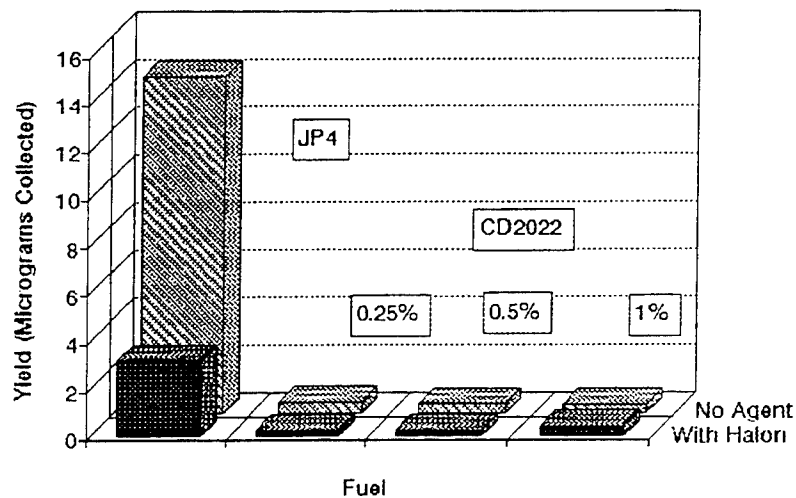


Figure 91. Relative collected masses of benzene with and without halon.

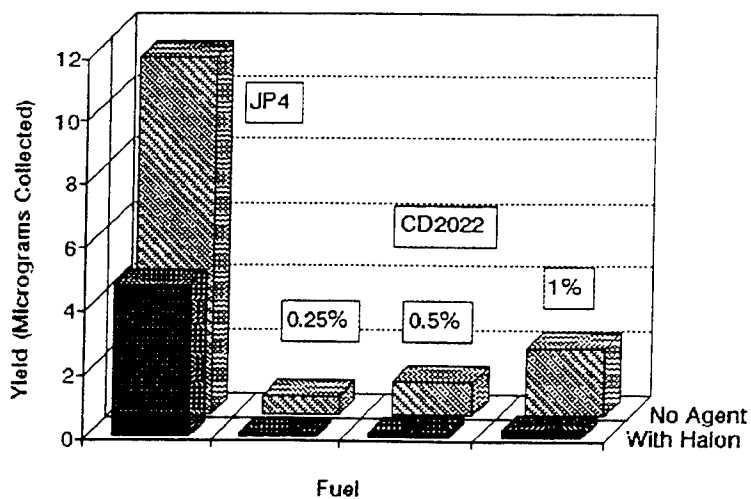


Figure 92. Relative collected masses of toluene with and without halon.

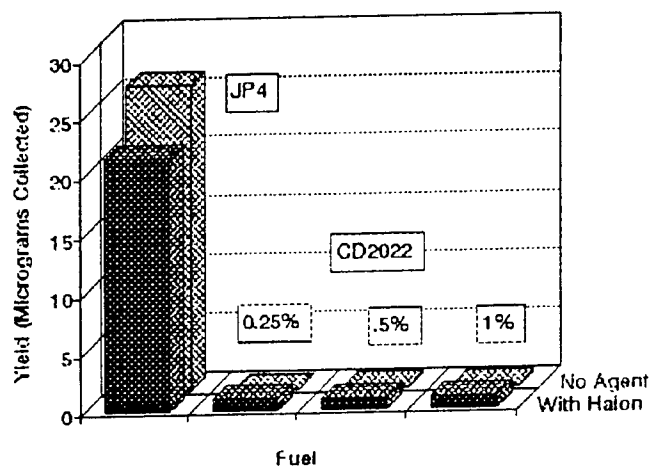


Figure 93. Measured naphthalene concentrations.

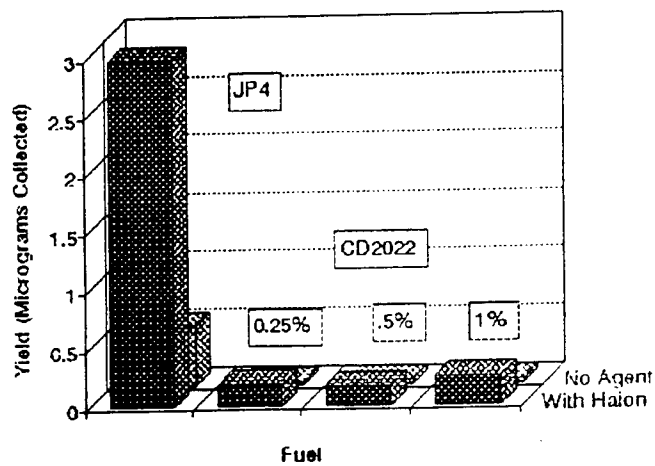


Figure 94. Measured acenaphthylene concentrations.

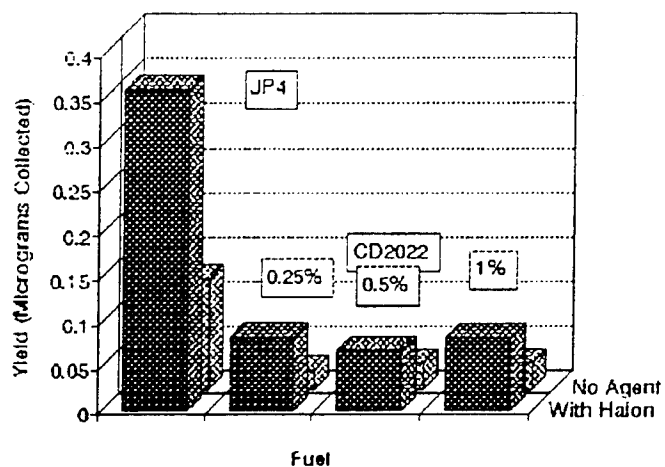


Figure 95. Measured 1,1-biphenyl concentrations.

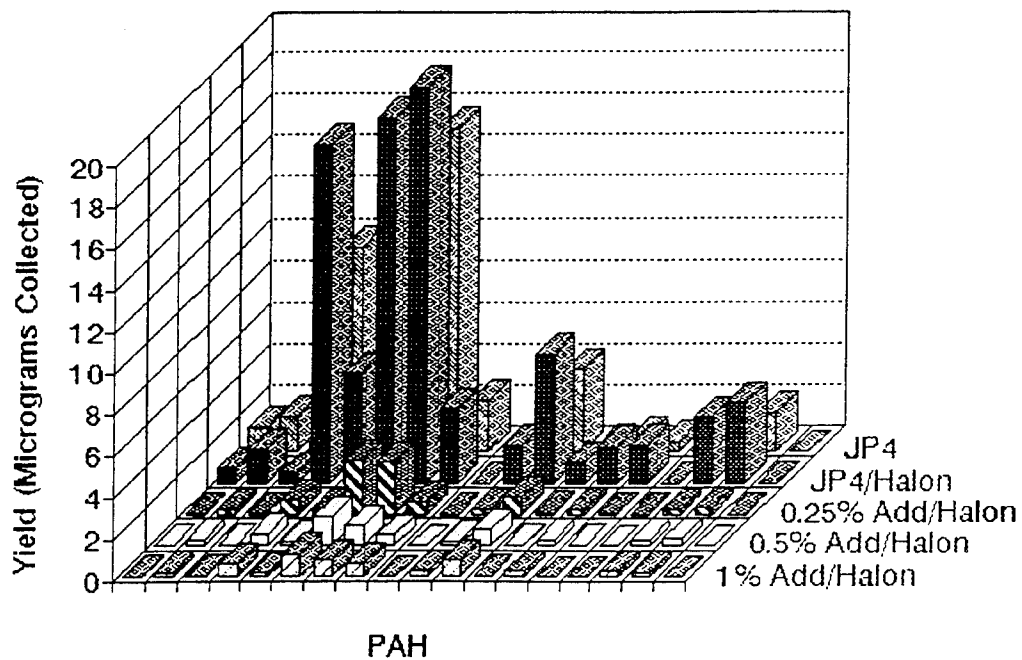


Figure 96. Relative collected masses of non-volatile PAH's with and without halon.

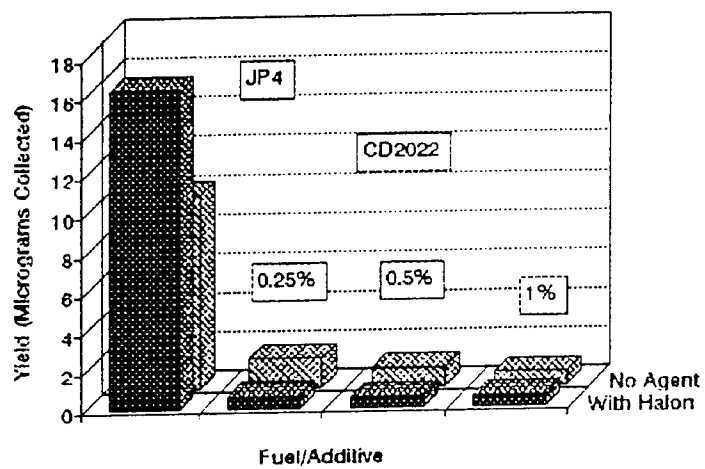


Figure 97. Measured phenanthrene concentrations.

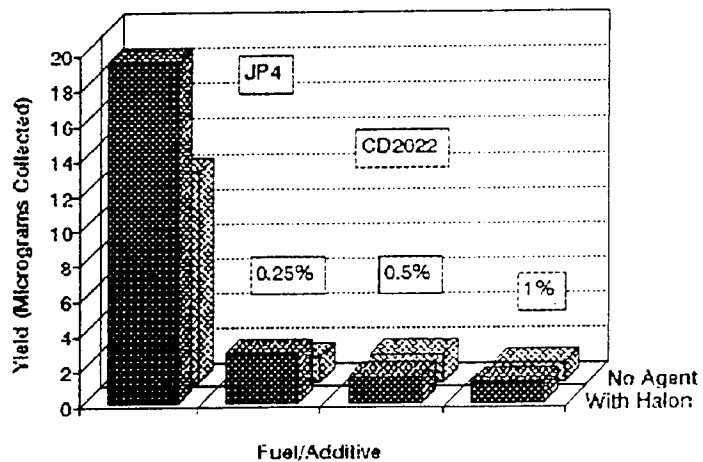


Figure 98. Measured fluoranthene concentrations.

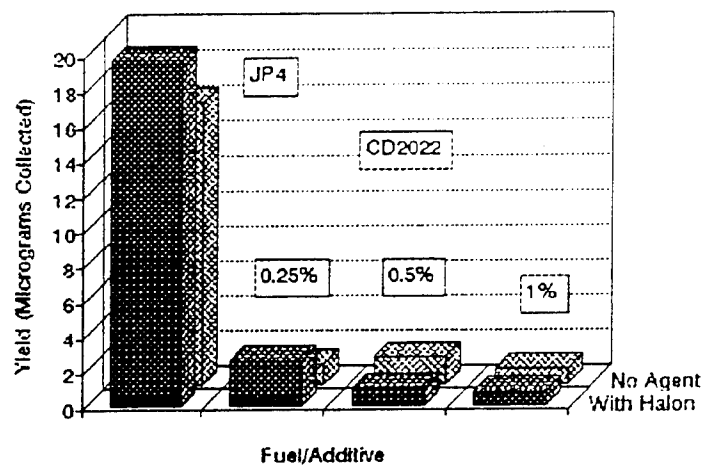


Figure 99. Measured pyrene concentrations.

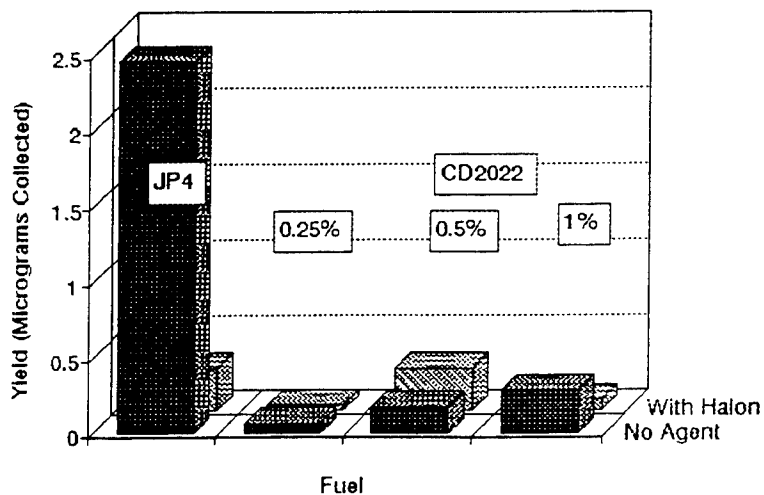


Figure 100. Relative collected masses of formaldehyde with and without halon.

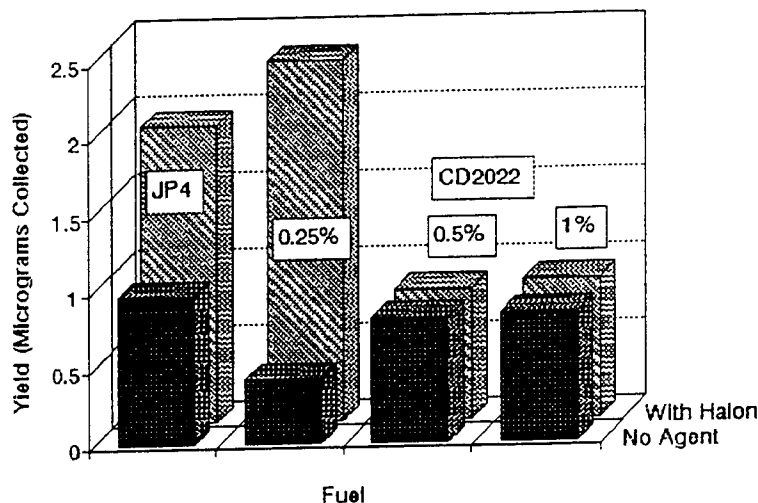


Figure 101. Relative collected masses of propionaldehyde with and without halon.

7. Halogenated Compounds.

Halons are known to decompose during combustion leading to the formation of halogenated compounds such as hydrogen fluoride (HF), hydrogen chloride (HCl) and hydrogen bromide (HBr). An attempt was made during these tests to detect a change in the acidity of the plume gases but it transpired that our sensitivity was not great enough to make any conclusions. Fourier Transform Infra-Red (FTIR) absorption measurements were performed by Applied Research Associates personnel in order to detect the presence of these compounds in the fire. Carbonyl chloride (COCl_2), otherwise known as phosgene, was detected when halon was used although the measurements were not quantitative and it was not possible to draw any fuel specific conclusions from this data.

SECTION VI

LARGE SCALE TESTS

A. INTRODUCTION

A series of large scale tests involving 20 foot and 100 foot diameter fires was performed, the tests being listed in Table 7. One hundred and ten gallons of fuel was used for each of the 20 foot fires and 500 gallons for the 100 foot fires. The purpose of this series was to examine visually the effects of scale upon the smoke emission, to compare fires of JP4 and CD2022 with additive and to allow firefighters to attack the fires, in order to determine the robustness of the new CD2022 fuel against extinguishment. Extensive video and still photographic records were collected during these tests and these are the primary source of data.

B. SMOKE EMISSION

Absolute measurements of smoke yield were not performed during these tests as they are not only difficult to perform accurately and reproducibly on such large fires but they would have interfered with the extinguishment trials. Tests were made using CD2022 with 0.25%, 0.5% and 1% additive and little visual difference in the results was observed for these three cases. It was found that smoke yields were greatly reduced compared with JP4 although the degree of smoke suppression did not seem to be just as high as in the small scale tests. This is very difficult to judge for smoke is extremely visible and even a small amount appears significant. The consensus of opinion from the observers however, was that this fuel/additive mixture represented a major advance over conventional aviation fuels and would be fuel that would prove to be environmentally acceptable in most training locations for the foreseeable future.

C. EXTINGUISHMENT

The 100 foot diameter fires were attacked by firefighters from both the US Air Force and the Canadian Air Force using Aqueous Film Forming Foam (AFFF) dispensed from an airport firetruck. It was found that the new fuel burned much longer and was harder to extinguish than JP4. (The extinguishment times are listed in Table 7). This is a major advantage for firefighter training for it provides more challenge to the trainee and allows the trainee more time to really appreciate what is happening during the extinguishment process.

D. RESIDUES

These tests were conducted with the fuel floating on top of water and following the fires, liquid samples were collected from the surface of the pool. Two of these samples, one taken following the JP4 fire and one from the CD2022 + 0.5% test were subjected to gas chromatography. The JP4 sample was dark in colour and showed a complex spectrum with many lines. The sample from the CD2022 + 0.5% fire looked very much like the original fuel and chromatographic analysis revealed peaks that were indeed characteristic of the original fuel/additive

mixture. Since the fuel composition is proprietary data, belonging to EXXON Chemical Ltd. these chromatograms are not shown in this document.

This is a very important factor from an operational viewpoint since the lack of solid residue following fires of CD2022 with additive will lead to considerable savings on fuel cleanup costs during fire training operations.

E. SUMMARY

The new CD2022 plus additive fuel performed very well during these tests and showed itself to be a great improvement on the conventional JP4 fuel. Indeed it can be said that it displayed all the characteristics required of a clean burning firefighter training fuel. Experience gained during these tests pointed to methods by which the smoke emission could be decreased even further by modifying the method of burning the fuel. These methods include atomizing the fuel using a nozzle array and using rings to confine the pool to an annular configuration thus allowing the core of the fire to receive more oxygen. These methods were tested by Air Force and Applied Research Associates personnel in a subsequent test series held in October 1993 and it was shown to be possible to operate this fuel essentially smoke free while still maintaining the realism inherent with a liquid fuel.

SECTION VII

SUMMARY AND CONCLUSIONS

The tests described in this report have shown that a proprietary new fuel, designated CD2022, when mixed with a smoke reducing additive, can produce emissions of particulate, VOC's, PAH's and Aldehydes that are very greatly reduced from those produced with conventional aviation fuels such as JP4, JP5 and JP8. Furthermore, while use of the smoke reducing additive does decrease emissions from these fuels, the size of these decreases is still inferior to that exhibited by the CD2022 fuel.

There is a lot of data in this report and in order to summarize it we shall concentrate on two cases only, JP4 and CD2022 + 0.5% additive. Table 19 provides a comparison of a number of specific emissions for these two fuels. The units used for this comparison are micrograms of compound detected per cubic meter of air sampled. Thus the data shown in the body of the report has been corrected for total burn times.

TABLE 19. COMPARISON OF SELECTED EMISSIONS FROM JP4 AND CD2022 + 0.5% ADDITIVE

Emission	JP4 (microgram/m ³)	CD2022 + 0.5% (microgram/m ³)
Soot	200,000	3,300
Benzene	93	2
Toluene	73	5.5
Naphthalene	167	0.4
Total Non-Volatile PAH	360	33
Formaldehyde	16.7	1

Table 20 lists the percentage measured reductions in these emissions for the cases of straight fuel fires and for the fires where firefighting agents were introduced.

TABLE 20. PERCENTAGE REDUCTIONS IN SPECIFIED EMISSIONS FROM FIRES OF JP4 AND CD2022 + 0.5% ADDITIVE COMPARED TO JP4

Emission	CD/ 0.5%	JP4/ AFFF	CD/ 0.5%/ AFFF	JP4/ Dry Chem	CD/ 0.5%/ Dry Chem	JP4/ Halon	CD/ 0.5%/ Halon
Soot	97%	13%	0%	N/A	N/A	-11%	87%
Benzene	97%	90%	98%	88%	98%	77%	98%
Toluene	91%	84%	97%	54%	97%	57%	99%
Naphthalene	99%	76%	99.7%	26%	99%	17%	96%
Total PAH	89%	14%	91%	-49%	94%	-56%	89%
Formaldehyde	93%	-116%	63%	-89%	81%	89%	89%

It is clear that the emission characteristics of the new fuel CD2022 + Additive during straight burning and under firefighting conditions are superior in all aspects to JP4.

SECTION VIII

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